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Edge Loading Has a Paradoxical Effect on Wear in Metal-on-Polyethylene Total Hip Arthroplasties

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Abstract

Background Edge wear is an adverse factor that can negatively impact certain THAs. In some metal-on-metal THAs, it can lead to adverse tissue reactions including aseptic lymphocytic vasculitis-associated lesions and even to pseudotumor formation. In some ceramic-on-ceramic THAs, it can lead to squeaking and/or stripe wear. Edge wear in metal-on-metal and ceramic-on-ceramic THAs can also be associated with accelerated wear across the articulation of these joints.

Questions/purposes I asked: Does edge wear occur in metal-on-polyethylene (MOP) articulations? And if so, does it increase joint wear?

Methods I examined the evidence in the literature for edge wear occurring in MOP THA and then assessed the evidence in the literature for data supporting the concept that edge wear in MOP hips could accelerate wear across the articulation over time.

Results Extensive data in the literature confirm edge wear is common in MOP THA. Surprisingly, the evidence does not support that it accelerates wear across the articulation. In fact, substantial data support the concept that it does not.

Conclusions These observations suggest, in terms of edge wear accelerating overall wear, MOP articulation may have a privileged position compared to hard-on-hard THA articulations.

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Introduction

Edge wear is defined as a local area of wear secondary to edge loading located at or near the edge of the acetabular component in THA. Edge wear may result from several different mechanisms. It is commonly related to impingement or associated with subluxation or dislocation. It may also be caused by microseparation and may be related to malposition of either the acetabular or femoral component or both or to unusually wide ROMs.

In metal-on-metal (MOM) articulations for THA, edge wear is recognized as a complicating factor that can lead to metallosis [10], adverse tissue reaction including aseptic lymphocytic vasculitis-associated lesions [30], and pseudotumor formation [13, 21], and in some cases, it is associated with accelerated wear of the entire articulation [7, 12], not just at the site of the edge wear. Similarly, for ceramic-on-ceramic (COC) THA articulations, in some studies, edge wear has been associated with squeaking [9, 11, 23, 29] and/or stripe wear [26, 30] of either the femoral head or the acetabular component or both, and in some situations, it can be associated with accelerated wear of the whole joint [17]. In view of the evidence showing edge wear in hard-on-hard bearings and the observation that it may produce accelerated wear of the articulation, it seemed reasonable to inquire whether these two phenomena, edge wear and accelerated general wear, occur with metal-on-polyethylene (MOP) THA joints.

I assessed the published literature to determine whether (1) edge loading was common in MOP THA joints and (2) edge wear would accelerate the general wear in those joints.

Search Strategy and Criteria

The literature search was limited to the years 1971 to 2011 and included only articles published in English. These dates were chosen because data of at least 9 years of followup appeared to be required to provide applicable quantitative information on changes in rates of wear or penetration over time. Shorter durations would likely be unable to provide evidence of statistically significant changes in rate during the steady-state period of penetration or wear after the bedding-in period, which included creep. These dates were also chosen for evaluating the question of edge loading in MOP THA because such data require either retrieval analysis or fluoroscopic analysis and it seemed most likely important data on this subject would be most prevalent after the first decade of experience with the UHMWPE, which was introduced in November 1962. The sources of data were (1) studies on edge loading in MOP THA, (2) studies on wear in MOP THA, and (3) studies on edge loading and wear in hard-on-hard THA.

The literature on whether or not edge loading occurred in MOP THA was reviewed. Because during the first four decades of THA the term edge loading was not commonly used, evidence of edge loading was also sought under other headings such as impingement and microseparation. Because the published literature on the occurrence of impingement/edge loading and edge wear in MOP THA was so voluminous, only illustrative examples of this question were included.

Data from long-term studies of wear of MOP articulations from the literature were evaluated to inquire whether the rates of general wear in MOP articulations accelerated over time after the phase of creep and/or bedding-in had ended. The literature on serial data on quantification of wear rates or penetration rates over durations of 9 years or more was selected from the literature on wear or penetration, including both radiographic and retrieval data. The inclusion criteria of the minimum of 9-year data and of the requirement for multiple serial data points sharply reduced the number of applicable reports. I used an Ovid Medline® search with the following parameters: (1) Hip Prosthesis/or hip.mp, (2) Polyethylene/, (3) 2 or polyethylene.mp, (4) 1 and 3, (5) wear.mp, (6) 4 and 6, (7) wear.ti. and 6, (8) limit 7 to (English and humans), (9) limit 8 to yr = "1971–2011". This search yielded 606 articles. If the titles suggested the possibility of pertinent data, the abstracts were read, and if the abstract appeared to contain data of possible utility, each article was read. In addition, my extensive reprint files were searched. Only seven publications (reporting on eight series of patients) on serial quantification of wear or penetration data met the criteria [2–5, 8, 20, 22] (Table 1). Also under the heading of microseparation, the experimental data were assessed on wear of the MOP THA joints, derived from modified hip simulators capable of modeling microseparation.

Data on the influence of edge loading in hard-on-hard THA bearings on general wear rates over time were gleaned from the literature from both clinical and experimental studies, searched over the years 2000 to 2011. Because the manuscript was not directed toward the influence of edge loading in MOM and COC THA, only illustrative papers on these subjects were included. I reviewed 113 articles and selected 30 as germane to the questions evaluated [1–14, 16, 17, 19–23, 25–33].

Results

Evidence for Edge Loading in MOP THA

Impingement is a common form of edge loading in MOP THA. Wroblewski [32] found impingement in 14 of 22 retrieved Charnley sockets (64%), while Birman et al. [1] noted 32% and Shon et al. [25] found 56%. Among the latter's findings was that 94% of those revised for recurrent dislocation had impingement, and in their overall group, 41% had impingement, despite more than ½ of the acetabular components being in acceptable position. Despite using larger-diameter heads up to 32 mm in size, the incidence of impingement was found by some studies to be likewise high and could be influenced by factors such as acetabular and/or femoral positions, polyethylene designs such as extended lip liners, etc. For example, Yamaguchi et al. [33] found, in a series of 111 retrieval MOP THA specimens, even using 32-mm heads, the incidence of impingement was 39% among all components, 94% of which had extended lip liners.

Impingement was also associated with another form of edge wear in that subluxation and/or recurrent dislocation generated edge loading not only at the dislocation site but also at the contre-coup site opposite the region of dislocation or subluxation [19].

Microseparation has been well demonstrated in MOP THA [16]. The relationship between microseparation, edge loading, and wear across the joint was evaluated

Table 1. Change in penetration rate or steady-state rate and wear rate in MOP THA from reports with duration of 9 years or greater

Study	Number of hips	Type of implant	Average age (years)	Duration (years)	Penetration or wear rate	Method of measurement	Findings
Charnley and Halley [2]	72	Charnley	63	9–10	Penetration	Charnley	Progressive decrease in rate until Year 4 and no increase thereafter
Issac et al. [8]	87	Charnley	55	9.25	Penetration	Shadowgraph of explants	No increase in penetration rate with time after the initial peak
Pedersen et al. [22]*	197	Charnley	66.3	10+	Wear	Iowa	No evidence of mid- or late-term acceleration of polyethylene wear; essentially constant wear rates for individual patients
Orishimo et al. [20]	31	AML® gamma sterilized	51.9	17	Wear	Martell	No evidence to support that wear rates were increasing for individual patients
	28	AML® ETO sterilized	54.7	14	Wear	Martell	No evidence to support that wear rates were increasing for individual patients
Dai et al. [3]	38	Omnifit®	56.7	10.9	Penetration	Two-dimensional computer method	No evidence to support that wear rates were increasing for individual patients
Goosen et al. [4]	93	Biomet® gamma-in-air sterilized	50	8.2 (3–12)	Wear	Livermore	Increase in wear rates after Year 6
Goosen et al. [5]	79	Biomet® gamma-in-argon sterilized	55	7.5 (3–12)	Wear	Livermore	No evidence to support that wear rates were increasing for individual patients

* Steady state refers to the rate after the bedding-in period; MOP = metal-on-polyethylene; AML® = Anatomic Medullary Locking; ETO = ethylene oxide.

experimentally by Fisher's group [26, 27, 31] using a model system that simulated microseparation in a modified hip simulator. Their model showed microseparation produced both edge wear and accelerated general wear in COC articulations, as well as in MOM joints using the same type of model [14]. In contrast, for MOP THA under the same experimental conditions, deformation occurred at the edge of the polyethylene acetabular component (plastic deformation and edge wear), but the overall wear of the articulation was not accelerated. Rather, it was decreased [31].

Relationship Between Edge Wear and Long-term Overall Wear Rates of MOP THA

Eight clinical studies from seven publications specifically addressed serial data on the wear rates or penetration rates of MOP THA, which permitted evaluation of changes in rates with time in patients [2–5, 8, 20, 22].

Radiographic data valid for penetration measurements from the report by Charnley and Halley [2] covered 9 to 10 years in 72 hips among patients whose average age was 63 years at the time of surgery using a 22-mm head against conventional UHMWPE involving the Charnley method of measuring penetration. It is likely these sockets had been sterilized chemically [8]. In their report, penetration peaked at about 1 year and thereafter progressively declined, with a continuing small rate of decrease after 4 years but no increase out to 10 years. When they subdivided the group into those with total penetration of up to 1.5 mm (the low- to average-wear group) versus those with total penetration of greater than 1.5 mm (the high-wear group), they found a similar pattern, namely a progressive decrease in penetration rate/year after the peak at about 1 year, but no evidence of an increase in wear at any time after the initial peak [2]. If one assumes the early penetration rate that peaked at about 1 year represented the sum of creep and wear and creep had largely ceased by the time of this peak, their data show no evidence of an acceleration of penetration rate in MOP THA over time, covering 10 years.

Isaac et al. [8] reported on 87 explanted nonirradiated Charnley hips in which penetration was assessed using a shadowgraph technique. The average implantation time was 9.25 years (range, 0.8–17.5 years) and the average age of the patients was 55 years (range, 19–73 years). In 83 of these hips, the revisions were performed for one or more loose components. The penetration rate was obtained by dividing the total penetration by the duration since implantation. The mean penetration rate in this series of retrievals was 0.204 mm/year (range, 0.005–0.6 mm/year), perhaps reflecting the influence of loose components or the higher rate of wear of conventional polyethylene sterilized without radiation. They found no increase in the penetration rate with time, after the initial peak involving both creep and wear.

The study of polyethylene wear rates from the University of Iowa [22], using the edge detection technique of analysis [24] was drawn from the analysis of 1237 radiographs in 197 patients performed by a single surgeon using Charnley implants and techniques. In that study, there was an average of 6.4 data points of wear/patient over a period averaging 10 years. After the bedding-in period, the authors found "essentially constant wear rates for individual patients" and added "there was no evidence of mid or late term acceleration of polyethylene wear" [22].

A fourth example is the data from an analysis of wear rates in two series of hips performed by Orishimo et al. [20], using the method of Martell and Berdia [18] In that study, they compared wear of gamma-irradiation-sterilized conventional polyethylene and ethylene oxide (ETO)-sterilized conventional polyethylene with radiographs every 2 years covering 17 years in the gamma-irradiated material and 14 years in the ETO-sterilized material. In these studies, all femoral heads were made of chrome-cobalt and had a 32-mm diameter. Their findings led them to conclude over time per patient there was "no evidence to suggest the wear rates were increasing" in either series [20].

One study [4] reported on penetration data in 93 primary MOP THAs in patients of an average age of 50 years using compression-molded UHMWPE against a chrome-cobalt 28-mm femoral head. From these data, they reported interval head penetration rates (which thus become wear rates) for 4 to 6 years, 7 to 9 years, and after 9 years, using the technique of Livermore et al. [15]. Their data showed an increase in median linear wear rates (millimeter/year) starting after Year 6, from 0.07 (range, 0–0.63) in Years 4 to 6 for 83 hips to 0.17 (range, 0–1.40) during Years 7 to 9 for 71 hips to 0.270 (range, 0–2.11) after 9 years in 24 hips.

In a subsequent study comparing wear rates of compression-molded conventional gamma-in-argon-sterilized UHMWPE from their 2005 publication [4], these same authors [5] showed the gamma-in-argon-sterilized UHMWPE showed no increase in wear rates over time. Another report [3] described serial wear measurements of 38 primary THAs in Japanese patients with an average age of 56.7 years and body weight of 53.3 kg using 22-mm femoral heads against gamma-in-air-sterilized UHMWPE over 10+ years, measured by a two-dimensional computerized assessment of the AP radiographs. After the bedding-in period, there was a progressive decline in wear rates and no rise in wear rate out to 10.9 years.

An experimental study of impingement and wear examining conventional irradiated polyethylene versus highly crosslinked polyethylene found the 10-MRad-irradiated material was more resistant to impingement than the conventional irradiated material, and the highly cross-linked polyethylene with edge wear produced by impingement had an overall wear rate of less than ½ of that of the conventional material [6].

Discussion

Current adverse tissue responses in certain MOM THAs and the presence of squeaking and stripe wear in COC THAs have focused attention on the importance of edge wear in these hard-on-hard articulations because these adverse factors are related in large measure to edge wear. This edge wear can be associated with acceleration of the general wear of the articulation. This focus on edge wear in hard-on-hard articulations prompted my investigation into the role of edge wear in causing accelerated overall wear of the polyethylene across MOP articulations.

The limitations of this study are several. The first is the assumption that the high frequency of impingement in MOP articulations in some series and the demonstration of microseparation on MOP articulations in a small group of patients are representative. A second assumption is, in those patients with edge loading, it occurs with sufficient frequency over long enough duration to cause edge wear, in contrast with a static demonstration at retrieval or the short-term demonstration in microseparation studies in vivo. A third assumption is the detection methods used to measure wear are refined enough to be able to identify changes in wear rate over time. In support of the possibility that the methods are refined enough to be able to provide this information is the fact that multiple different methods were reported here, ranging from shadowgraphy [8] to the radiographic methods of Charnley and Halley [2], Livermore et al. [15], Martell and Berdia [18], and the University of Iowa [24]. Finally, none of these studies addressed specifically the issue of malposition of the femoral or acetabular components or both. However, if anything, malposition of a component or components would likely increase rather than decrease the edge loading. Also, despite that limitation, increase in wear was detected in only one of the eight series.

The evidence strongly supports edge loading and the resulting edge wear are widespread phenomena in MOP articulations. The occurrence of these common phenomena was not associated with detectable increases in the overall penetration rate or wear rate of the femoral head into the polyethylene in vivo in seven of the eight series of serial wear rates or penetration rates. This observation was supported by clinical data involving unirradiated conventional polyethylene and gamma-irradiated conventional polyethylene and by one experimental study of one crosslinked polyethylene. The counterface metals used in the clinical studies showing no increase in wear rates were either stainless steel or chrome-cobalt femoral heads. The head sizes involved in these studies ranged from 22 to 32 mm.

Of note in the one report that found an increase in penetrations of the head into the polyethylene after Year 6 is the unusually high rates of penetration reported, leading to median penetration rates of 0.27 mm/year after 9 years in the 2005 report [4] and 0.42 mm/year after 9 years in the 2009 report [5], while the corresponding early penetration rates after creep had ceased were 0.07 mm/year at 4 to 6 years in the first study [4] and 0.14 mm/year at 4 to 6 years in the second study [5]. No other authors have published data on increasing rates of penetration with time after the bedding-in period, and none have shown median linear wear rates of these magnitudes at those durations. Those authors suggest these changes might be based on mechanical degradation over time based on oxidation, but no evidence was presented in these cases to establish oxidation or its effect on wear.

From experimental studies of microseparation in the hip simulator, Fisher's group [26, 27, 31] showed the microseparation form of edge loading used in their experimental model accelerated wear of the overall articulation with both MOM and COC articulations. Importantly, the results of similar studies using MOP articulations were exactly the opposite. These studies showed the wear at the articulation of the MOP joints was actually decreased compared to similar studies without the addition of microseparation. Furthermore, studies from that same group also compared microseparation versus no microseparation in the hip simulator using a ceramic femoral head against conventional polyethylene material [31]. In this comparison, they found reduced wear of the polyethylene articulation under conditions of microseparation compared to identical studies without the microseparation.

Thus, these data confirm edge loading is common in MOP articulations. In contrast, the bulk of the data suggest edge loading in MOP articulations and its resulting edge wear do not accelerate overall wear of the joint. Thus, in relation to the specific question of an increase in wear of the joint in MOP THA articulations secondary to edge loading, the MOP articulation appears to have a privileged position.

While the data presented here might represent a form of "forgiveness" in MOP THAs in terms of impingement and edge wear relative to the overall acceleration of penetration of the head into the polyethylene, no data in the literature reduce the importance of persistent and sustained efforts to reduce or eliminate impingement and/or edge loading.

References

1. Birman MV, Noble PC, Conditt MA, Li S, Mathis KB. Cracking and impingement in ultra-high-molecular-weight polyethylene acetabular liners. *J Arthroplasty.* 2005;20:87–92.
2. Charnley J, Halley DK. Rate of wear in total hip replacement. *Clin Orthop Relat Res.* 1975;112:170–179.
3. Dai X, Omori H, Okumura Y, Ando M, Oki H, Hashimoto N, Baba H. Serial measurement of polyethylene wear of well-fixed cementless metal-backed acetabular component in total hip arthroplasty: an over 10 year follow-up study. *Artif Organs.* 2000;24:746–751.
4. Goosen JH, Verheyen CC, Kollen BJ, Tulp NJ. In vivo wear reduction of argon compared to air sterilized UHMW-polyethylene liners. *Arch Orthop Trauma Surg.* 2009;129:879–885.
5. Goosen JH, Verheyen CC, Tulp NJ. Mid-term wear characteristics of an uncemented acetabular component. *J Bone Joint Surg Br.* 2005;87:1475–1479.
6. Holley KG, Furman BD, Babalola OM, Lipman JD, Padgett DE, Wright TM. Impingement of acetabular cups in a hip simulator: comparison of highly cross-linked and conventional polyethylene. *J Arthroplasty.* 2005;20:77–86.
7. Hussain A, Counsell L, Kamali A. Clinical effects of edge loading on metal-on-metal hip resurfacings. *J Bone Joint Surg Br.* 2010;92(suppl III):399.
8. Isaac GH, Dowson D, Wroblewski BM. An investigation into the origins of time-dependent variation in penetration rates with Charnley acetabular cups—wear, creep or degradation? *Proc Inst Mech Eng H.* 1996; 210:209–216.
9. Jarrett CA, Ranawat AS, Bruzzone M, Blum YC, Rodriguez JA, Ranawat CS. The squeaking hip: a phenomenon of ceramic-on-ceramic total hip arthroplasty. *J Bone Joint Surg Am.* 2009;91: 1344–1349.
10. Jones DA, Lucas HK, O'Driscoll M, Price CH, Wibberley B. Cobalt toxicity after McKee hip arthroplasty. *J Bone Joint Surg Br.* 1975;57:289–296.
11. Keurentjes JC, Kuipers RM, Wever DJ, Schreurs BW. High incidence of squeaking in THAs with alumina ceramic-on-ceramic bearings. *Clin Orthop Relat Res.* 2008;466:1438–1443.
12. Langton DJ, Jameson SS, Joyce TJ, Hallab NJ, Natu S, Nargol AV. Early failure of metal-on-metal bearings in hip resurfacing and large-diameter total hip replacement: a consequence of excess wear. *J Bone Joint Surg Br.* 2010;92:38–46.
13. Langton DJ, Joyce TJ, Jameson SS, Lord J, Van Orsouw M, Holland JP, Nargol AV, De Smet KA. Adverse reaction to metal debris following hip resurfacing the influence of component type, orientation and volumetric wear. *J Bone Joint Surg Br.* 2011;93: 164–171.
14. Leslie IJ, Williams S, Isaac G, Ingham E, Fisher J. High cup angle and microseparation increase the wear of hip surface replacements. *Clin Orthop Relat Res.* 2009;467:2259–2265.
15. Livermore J, Ilstrup D, Morrey B. Effect of femoral head size on wear of the polyethylene acetabular component. *J Bone Joint Surg Am.* 1990;72:518–528.

16. Lombardi AV Jr, Mallory TH, Dennis DA, Komistek RD, Fada RA, Northcut EJ. An in vivo determination of total hip arthroplasty pistoning during activity. *J Arthroplasty.* 2000;15:702–709.
17. Lusty PJ, Watson A, Tuke MA, Walter WL, Walter WK, Zicat B. Wear and acetabular component orientation in third generation alumina-on-alumina ceramic bearings: an analysis of 33 retrievals [corrected]. *J Bone Joint Surg Br.* 2007;89:1158–1164.
18. Martell JM, Berdia S. Determination of polyethylene wear in total hip replacements with use of digital radiographs. *J Bone Joint Surg Am.* 1997;79:1635–1641.
19. Nadzadi ME, Pedersen DR, Yack HJ, Callaghan JJ, Brown TD. Kinematics, kinetics, and finite element analysis of commonplace maneuvers at risk for total hip dislocation. *J Biomech.* 2003;36:577–591.
20. Orishimo KF, Hopper RH Jr, Engh CA. Long-term in vivo wear performance of porous-coated acetabular components sterilized with gamma irradiation in air or ethylene oxide. *J Arthroplasty.* 2003;18:546–552.
21. Pandit H, Glyn-Jones S, McLardy-Smith P, Gundle R, Whitwell D, Gibbons CL, Ostlere S, Athanasou N, Gill HS, Murray DW. Pseudotumours associated with metal-on-metal hip resurfacings. *J Bone Joint Surg Br.* 2008;90:847–851.
22. Pedersen DR, Brown TD, Hillis SL, Callaghan JJ. Prediction of long-term polyethylene wear in total hip arthroplasty, based on early wear measurements made using digital image analysis. *J Orthop Res.* 1998;16:557–563.
23. Restrepo C, Matar WY, Parvizi J, Rothman RH, Hozack WJ. Natural history of squeaking after total hip arthroplasty. *Clin Orthop Relat Res.* 2010;468:2340–2345.
24. Shaver SM, Brown TD, Hillis SL, Callaghan JJ. Digital edge-detection measurement of polyethylene wear after total hip arthroplasty. *J Bone Joint Surg Am.* 1997;79:690–700.
25. Shon WY, Baldini T, Peterson MG, Wright TM, Salvati EA. Impingement in total hip arthroplasty: a study of retrieved acetabular components. *J Arthroplasty.* 2005;20:427–435.
26. Stewart T, Tipper J, Streicher R, Ingham E, Fisher J. Long-term wear of HIPed alumina on alumina bearings for THR under microseparation conditions. *J Mater Sci Mater Med.* 2001;12:1053–1056.
27. Stewart T, Williams S, Tipper J, Ingham E, Stone M, Fisher J. Advances in simulator testing of orthopaedic joint prostheses. In: Dowson D, Priest M, Dalmaz G, Lubrecht AA, eds. *Tribological Research and Design for Engineering Systems. Proceedings of the 29th Leeds-Lyon Symposium (Tribology and Interface Engineering).* 2003:291–296.
28. Walter WL, Insley GM, Walter WK, Tuke MA. Edge loading in third generation alumina ceramic-on-ceramic bearings: stripe wear. *J Arthroplasty.* 2004;19:402–413.
29. Walter WL, Yeung E, Esposito C. A review of squeaking hips. *J Am Acad Orthop Surg.* 2010;18:319–326.
30. Willert HG, Buchhorn GH, Fayyazi A, Flury R, Windler M, Koster G, Lohmann CH. Metal-on-metal bearings and hypersensitivity in patients with artificial hip joints: a clinical and histomorphological study. *J Bone Joint Surg Am.* 2005;87:28–36.
31. Williams S, Butterfield M, Stewart T, Ingham E, Stone M, Fisher J. Wear and deformation of ceramic-on-polyethylene total hip replacements with joint laxity and swing phase microseparation. *Proc Inst Mech Eng H.* 2003;217:147–153.
32. Wroblewski BM. Direction and rate of socket wear in Charnley low-friction arthroplasty. *J Bone Joint Surg Br.* 1985;67:757–761.
33. Yamaguchi M, Akisue T, Bauer TW, Hashimoto Y. The spatial location of impingement in total hip arthroplasty. *J Arthroplasty.* 2000;15:305–313.