PARTICULATE DEBRIS IN TOTAL HIP ARTHROPLASTY: PROBLEMS AND SOLUTIONS

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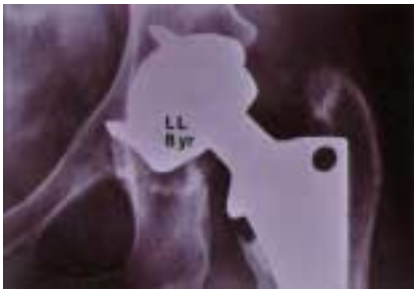
INTRODUCTION

There is acute concern, particularly with noncemented implants, about polymeric and metallic debris generation and accumulation in total hip arthroplasty and its association with osteolysis and implant loosening. The purpose of this paper is to describe the problems associated with particulate debris, the sources of particulate debris in THA, and potential solutions or approaches to minimize particle formation.

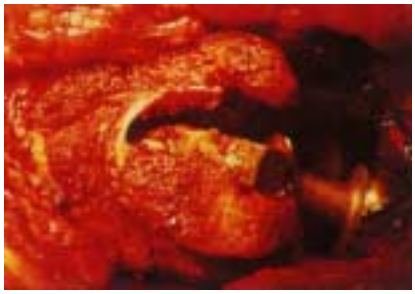
BASIC PROBLEMS

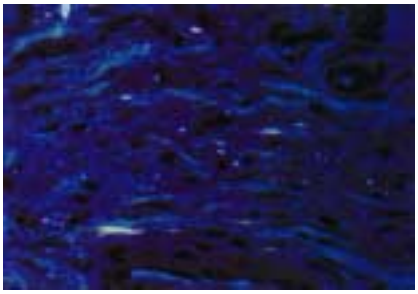
Polymeric Debris

It has been almost two decades since Willert first described the problem of polyethylene wear leading to peri-prosthetic inflammation, granuloma, bone resorption, and implant loosening.' Since then, many studies have documented the finding of particulate bone cement and polyethylene in peri-prosthetic tissues.[2-4] The underlying biologic mechanism is thought to be mediated by the activity of macrophages which, upon ingestion of foreign material, release a number of factors (prostaglandins, interleukins) that stimulate osteoclastic activity.[5-7] Particles less than about 10 microns are more important in this mechanism because they are most easily phagocytosed by macrophages.[8,9] Histologic study of synovium and granuloma biopsies from THA has shown intracellular polyethylene particles in the sub-micron size range.[10-12]



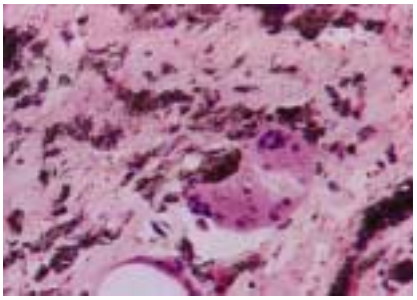
Eccentric cup wear with acetabular and proximal femoral osteolysis 8 yrs; postop


Proximal femoral cavity from polyethylene granuloma 4 yrs postop


Polarized light micrograph showing intracellular and extracellular PE debris

Metallic Debris

Metallic particles in sufficient quantities could potentially activate macrophage-mediated osteolysis. Metal debris could also migrate into the articulation, scratch the femoral head, and cause increased third-body wear of polyethylene.


Intracellular and extracellular metal debris in capsule 6 yrs postop


Scratches in polyethylene liner from abrasive third-body wear

SOURCES OF POLYETHYLENE DEBRIS

PROBLEM: Wear Related to Polyethylene Quality

In normally wearing artificial joints, linear wear rates of 0.05 to 0.2 mm per year result in the generation of about 25 to 100 mm^3 (25 to 100 mg) of polyethylene debris annually.[13-15] On the basis of known dimensions of polyethylene particles found in tissues around hip prostheses, this equates to the annual production of tens to hundreds of billions of particles.

Variations in polyethylene wear rates probably relate, at least in part, to the quality of the polyethylene used.[15] Wide variations are known to exist between batches of polyethylene and between different polyethylene suppliers.

SOLUTION:

Use ultra high molecular weight polyethylene (UHMWPE) with high ratings in key mechanical and physical properties (Table 1). Use UHMWPE with a consistently high level of quality control over parameters such as starting powder composition, extrusion processing (extruded rod generally results in better consolidation and improved properties compared with compression molded UHMWPE sheets), post-extrusion annealing (to increase crystallinity and dimensional stability), ultrasound inspection for voids and inclusions, oxidation, and mechanical properties. In general, polyethylene that exceeds minimum ASTM standards is available from several implant manufacturers (Table 1).

Table 1. Properties of UHMWPE

	ASTM Standard	Commercially Available PE[16]	Commercially Available PE[17]
Molecular Weight	3 x 10^6	5 x 10^6	–
Ultimate Tensile Strength	4000 PSI	6700 PSI	6000 PSI
Tensile Yield	2800 PSI	3300 PSI	4100 PSI
Izod Impact	20 FT-LB	No Break	No Break
Hardness	60 Shore D	69 Shore D	65 Shore D
Elongation to Failure	200%	350%	330%

PROBLEM: Polyethylene Wear Related to Modular Acetabular Implants

Additional sources of polyethylene wear can result from the use of modular (2-piece) acetabular implants."-" These include:

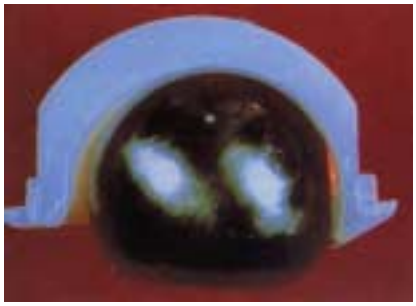
Polyethylene liner/metal back motion - related to mechanical integrity of the locking mechanism

Incomplete conformity of liner with metal back can result in cold flow, plastic deformation, increased stress, increased wear

Thin polyethylene resulting from modular design can cause higher stress, increased wear, liner fracture

Liner fracture 4 yrs postop, head wear of cup metal backing, tissue metallosis

Abrasion of screw heads against the convex polyethylene surface

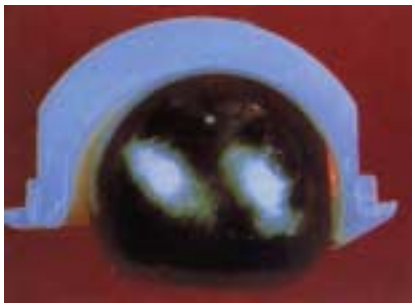


SOLUTIONS:

- Use non-modular acetabular components
- Use modular acetabular components with:
  - high degree of liner/metal back conformity and support (with smooth concave metal surface to minimize abrasive wear)
  - highly secure liner/metal back locking mechanism
  - minimum polyethylene thickness of 6 to 8 MM[22,23]

PROBLEM: Polyethylene Wear Related to Femoral Head Size

Clinical evidence indicates that the use of 32 mm heads in THA increases the volumetric wear. This problem is accentuated with cups possessing relatively thin polyethylene, as occurs with smaller size modular prostheses.



SOLUTION:

A recent clinical study by Livermore et al indicated that a 28 mm head size was preferred for optimization of both linear and volumetric wear.[24] Choosing head size to maximize polyethylene thickness is a priority. The recommendation is to use 26 mm or 28 mm heads more often, although 32 mm heads are still appropriate with larger cups having thick polyethylene.

PROBLEM: Polyethylene Wear Related To Femoral Head Material

Polyethylene wear is generally increased with the use of femoral heads made of titanium alloy because of its lower hardness and abrasion resistance. Problems with osteolysis due to excessive head and cup wear have been reported with titanium bearing surfaces.[25-27]

SOLUTIONS:

- Do not use titanium alloy femoral heads
- Use titanium alloy femoral heads with improved wear characteristics. This can be accomplished by shallow implantation of nitrogen or oxygen into the surface or chemical deposition of a harder bearing surface such as titanium nitride.
- A preferred option is to use femoral heads made of cobalt-chrome because of its superior wear characteristics.
- Laboratory evidence supports the use of femoral heads made from ceramic materials, alumina or zirconia oxide, for reduced polyethylene wear. Preliminary clinical evidence from Europe and Japan suggests a reduced wear rate in patients but the data are not yet definitive.[30-33] At the very least, ceramic bearing materials are more resistant to scratching from third bodies such as PMMA or metallic debris from fretting, corrosion, or loosened fragments of porous coating.
- Based on favorable clinical trials in Europe during the past decade, improved ceramic-on-ceramic and metal-on-metal bearing combinations have been renewed as possible solutions to the problem of polyethylene wear.[34] Further research and development in this area will be required to establish reliability and efficacy.

SOURCES OF METALLIC DEBRIS

PROBLEM: Fretting Wear of Metallic Implant Components

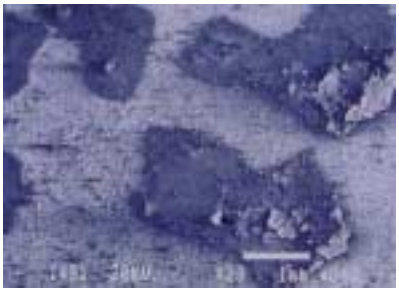
Fretting wear of mechanically joined metallic implant components is inevitable given sufficient load and number of load cycles.[35-38] Thus, all modular implant junctions are prone to fretting and the generation of metallic debris. This includes:

- Junctions between screws and metal backing of modular cups
- Head/neck taper junctions
- Other stem modular junctions utilizing locking mechanisms such as tapers or dovetails to connect sleeves, pads, or stem segments.

Fretting marks on Ti-6AI-4V taper 4 yrs postop

Scanning electron micrograph of fretting marks on Ti-6AI-4V taper

Small areas of fretting on modular stem taper 6 yrs postop



Scanning electron micrograph of fretting scars on modular stem taper

SOLUTIONS

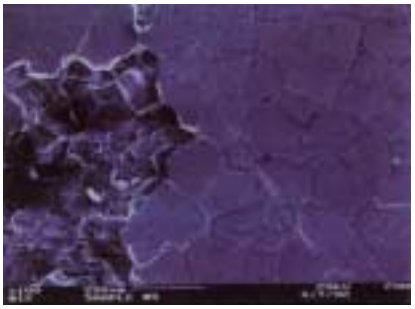
- Minimize the number of modular junctions (e.g., use cups without screw holes or reduce use of screws for acetabular cup fixation)
- Use modular junctions with secure locking mechanisms, high quality fabrication tolerances, surface finishes that reduce debris generation, and proven mechanical safety in laboratory testing.

PROBLEM: Corrosion at Head/Neck Taper Junctions

Recent analysis of retrieved femoral implants used in THA has revealed that corrosion sometimes occurs at the modular head/neck junction.[39-41] Corrosion in varying degrees has been reported both with dissimilar (Co-Cr head/Ti alloy neck) and similar (Co-Cr head/Co-Cr neck) metal combinations. The corrosion problem has not been the cause of clinical failure except in a few rare cases with Co-Cr/Co-Cr tapers that have fractured. Galvanic corrosion, crevice corrosion, and fretting corrosion have all been suggested as mechanisms that are responsible for this problem.[39-43]

Corrosion on mixed-metal taper 22 months postop

Corrosion on Co-Cr/Co-Cr taper 10 yrs postop

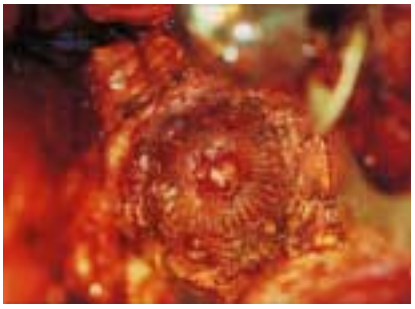


SEM showing intergranular corrosion and grain loss with a Co-Cr taper 10 yrs postop

SOLUTIONS:

For head/neck tapers with dissimilar metals, the risk of corrosion can be reduced by using tapers with tight manufacturing tolerances. This reduces fluid ingress and the extent of fretting which could trigger corrosion by depassivating the protective metallic oxide layers and setting up a crevice corrosion cell.[37,42,43] In response to the corrosion problem, the orthopaedic implant industry is improving the tolerances and quality control of head/neck tapers.

- For all modular tapers, lock the femoral head onto the neck with adequate force. It is helpful to initially twist the femoral head into position and then apply 3 or 4 seating taps. Ensure that both male and female surfaces are clean and dry prior to assembly.
- For tapers on Co-Cr stems, in addition to high quality manufacturing, ensure that heat treatments used to apply porous coatings do not create intergranular zones that are prone to corrosive attack and eventual mechanical failure.[44]

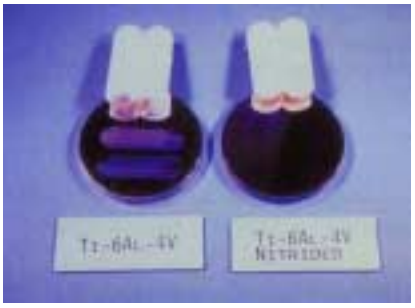


Metal-stained acetabulurn after removal of loose Ti-6AI-4V cup

PROBLEM: Particulate Release Through Implant Bone-Abrasion

Noncemented implants which move relative to the implant site can release particulate debris through simple abrasion mechanisms. This problem is worse with Ti-based implants because of lower hardness and abrasion resistance.[45] Furthermore, cosmetic implant preparation techniques such as bead blasting tend to leave residual contaminants (silica or alumina) and create tenuous surface irregularities -these are prone to being dislodged by abrasion against bone.

Reduced wear of nitrided Ti alloy abraded against PMMA & cortical bone (pin on disk)



Scanning electron micrograph of bead blasted Ti-6AI-4V implant

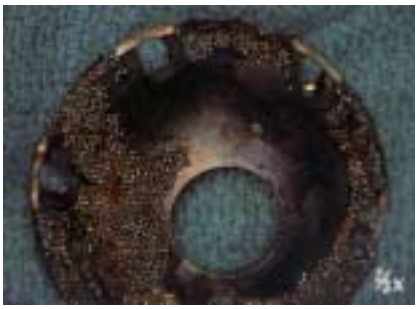
SOLUTIONS:

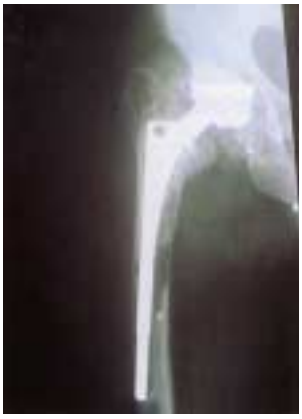
- Increase the surface hardness and abras 0 n resistance of Ti-based implants through creat!on of a surface-rich zone of nitrogen or oxygen.
- Increase the cleanliness and smoothness of implant surfaces by avoiding grit-blasting or sand-blasting. Instead, leave the implant surface simply polished or cleaned and micro-etched with chemical-milling techniques.[45-48]
- Use noncemented implants with design features that maximize the opportunities for stability, thereby minimizing the risk of interface micromotion and abrasion.

SEM of polished and nitrided Ti alloy to reduce metallic particulate debris

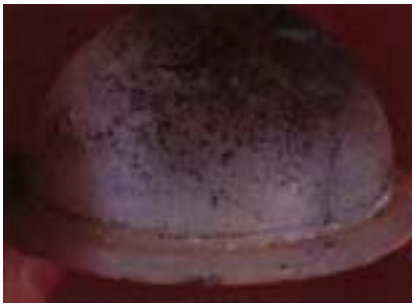
PROBLEM: Third-Body Wear From Debonded Porous Coating

There are numerous reports of loosened fragments of porous coating migrating into the joint space and causing third-body wear of the bearing surfaces.[49-51] This problem has also been reported with loosened fragments of hydroxyapatite coating.[52,53] Excessive polyethylene wear can result in particulate debris-induced granuloma, bone loss, implant loosening, and revision.





Loose stem, debonded porous coating, 3-body cup wear, marked polyethylene granuloma



Debonded porous coating fragments embedded in PE liner - fragments migrated through screw holes of metal backing

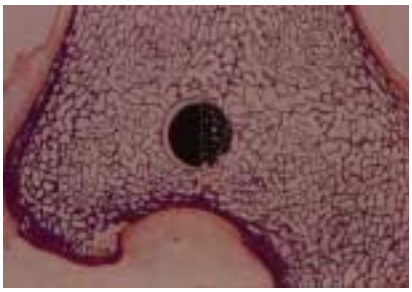
SOLUTIONS:

- Use noncemented implants with well-bonded porous coatings and a proven history of use without this problem. In general, metallic porous coatings with metallurgical bonds (e.g., diffusion bonded or sintered) are more mechanically resistant than metallic or calcium phosphate coatings applied with plasma spray techniques.
- Use noncemented implants with design features that increase the likelihood of secure fixation. Coatings debond more easily in the presence of motion.

MIGRATION OF PARTICULATE DEBRIS

PROBLEM:

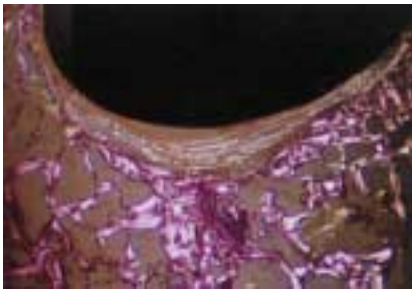
Regardless of origin, through the cyclic pumping action of joint pressure, polymeric or metallic debris can migrate throughout the effective joint space, accessing bone-implant interfaces and articulating surfaces.[4,54] Particle migration has been documented with both cemented and noncemented implants.



Canine knee implant model with chronic PE injections. Result: fibrous membrane around the smooth implant half only[57]

SOLUTIONS:

- For noncemented hip prostheses, it has been suggested that circumferential porous coating will allow more complete tissue ingrowth and help restrict the access of particulate material along bone-implant interfaces.[6,55] There is experimental evidence to support the theory that smooth implant interfaces allow greater access of polyethylene debris. [56,57]
- Press-fitting of noncemented acetabular implants results in a tight peripheral fit which may impede access of particulate debris to the bone prosthesis interface.[58]
- Minimize the overall generation of particulate debris through all of the above recommendations.



Canine knee implant model.[57] PE particles within fibrous membrane on smooth implant half only (polarized light)

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REFERENCES

1. Willert, H.G. and Semlitsch, M.: Reactions of the articular capsule to wear products of artificial joint prostheses. J. Biomed. Meter. Res. 11:157, 1977.

2. Howie, D.W.: Tissue response in relation to type of wear particles around failed hip arthroplasties. J. Arthrop. 5:337, 1991.

3. Schmalzried, T.P., Kwong, L.M., Jasty, M., et al: The mechanism of loosening of cemented acetabular components in total hip arthroplasty: analysis of specimens retrieved at autopsy. Clin. Orthop. Rel. Res. 274:60, 1991.

4. Schmalzried, T.P., Jasty, M., Harris, W.H.: Periprosthetic bone loss in THA. Polyethylene wear debris and the concept of the effective joint space. J. Bone Joint Surg. 74A:849, 1992,

5. Amstutz, H.C., Campbell, P., Kossovsky, N., Clarke, I.: Mechanism and clinical significance of wear debris-induced osteolysis. Clin. Orthop. 276:7, 1992.

6. Anthony, P.P., Gie, G.A., Ling, R.M.: Localised endosteal bone lysis in relation to the femoral components of cemented total hip arthroplasties. J. Bone Joint Surg. 72B:971, 1990.

7. Santavirta, S., Hoikka, V., Eskola, A. et al.: Aggressive granuionnatous lesions in cementless total hip arthroplasty. J. Bone Joint Surg. 7213:980, 1990.

8. Murray, D.W. and Rushton, N.: Macrophages stimulate bone resorption when they phagocytose particles. J. Bone Joint Surg. 7213:988, 1990.

9. Chiba, J., Maloney, W., Horikoshi, M., McIntyre, L., Rubash, H.: Biochemical and morphological analyses of activated human macrophages and fibroblasts by human Polyethylene particles. Trans. of 39th Ann. Meet. of Orthop. Res. Soc., San Francisco, 1993.

10. Kossovsky, N., Liao, K., Gelman, A., Millet, D.,; Size and mass quantification of sub-micron particulates in human synovial tissues recovered at revision. Proc. of Ann. Meet. of Soc. for Bionnat. 1991, p. 242.

11. Maloney, W.J., Smith, R.L., Huene, D., Rubash, H.: Particulate wear debris: characterization and quantitation from membranes around failed cementless femoral replacements. Trans. of 39th Ann. Meet. of Orthop. Res. Soc., San Francisco, 1993.

12. Shanbhag, A.S., Giant, T.T., Gilbert, J.L., Black, J., Galante, J.O.: Chemical and morphological characterization of wear debris in failed uncemented total hip replacement. Trans. of 39th Ann. Meet. of Orthop. Res. Soc., San Francisco, 1993.

13. Wroblewski, B.M.: Direction and rate of socket wear in Charnley low-friction arthroplasty. J. Bone Joint Surg. 6713:757, 1985.

14. Rimnac, C.M., Wilson, P.D., Jr., Fuchs, M.D., Wright, T.M.: Acetabular cup wear in total hip arthroplasty. Orthop. Clin. North AM. 19:631, 1988.

15. Wright, T.M. and Rimnac, C.M.: Ultra-high-molecular-weight polyethylene. In: Joint Replacement Arthroplasty (Morrey, B.F., ed.) Churchill Livingstone, New York, 1991, pp. 37-45.

16. Hawkins, M.E.: Ultra high molecular weight polyethylene. Zimmer technical report, February 1993.

17. Depuy, Inc., Warsaw, Indiana: A new enhanced ultra high molecular weight polyethylene for orthopaedic applications: a technical brief. 1989.

18. Tradonsky, S., Postak, P.D., Froinnson, A.L, Greenwald, A.S.: Performance characteristics of two-piece acetabular cups. Scientific Exhibit, AAOS, 1991, p. 246.

19. Kitziger, K.J,, DeLee, J.C., Evans, J.A.: Disassembly of a modular acetabular component of a total hip arthroplasty. J. Bone Joint Surg. 72A:621, 1990.

20. Huk, O.L., Bansal, M., Betts, F., et al: Generation of polyethylene and metal debris from cementless modular acetabular components in total hip arthroplasty. Trans. of 39th Ann. Meet. of Orthop. Res. Soc., San Francisco, 1993.

21. Kurtz, S.M., Gabriel, S.M., Bartel, D.L.: The effect of non-conformity between metal-backing and polyethylene inserts in acetabular components for total hip arthroplasty. Trans. of 39th Ann. Meet. of Orthop. Res. Soc., San Francisco, 1993.

22. Connelly, G., Rimnac, C., Wright, T., et al.: Fatigue crack propagation behavior of ultrahigh molecular weight polyethylene. J. Orthop. Res. 2:119, 1984.

23. Bartel, D.L., Bickwell, V.L., Wright, T.M.: The effect of conformity, thickness and material on stresses in ultra-high molecular weight components for total joint replacement. J. Bone Joint Surg. 68A:1041, 1984.

24. Livermore, J., Ilstrup, D., Morrey, B.: Effect of femoral head size on wear of the polyethylene acetabular component. J. Bone Joint Surg. 72A:518, 1990.

25. Brien, W.H., Salvati, E.A., Betts, F. et al.: Metal levels in cemented total hip arthroplasty. A comparison of well-fixed and loose implants. Clin. Orthop. 276:66, 1992.

26. Lombardi, A.V., Mallory, T.H., Vaughn, B.K., Drouillard, P.: Aseptic loosening in total hip arthroplasty secondary to osteolysis induced by wear debris from titanium-alloy modular femoral heads. J. Bone Joint Surg. 71A:1337, 1989.

27. Agi ns, H.J., Alcock, N.W., Bansal, M., et al.: Metallic wear in failed titan iu m-alloy total hip replacements. A histological and quantitative analysis. J. Bone Joint Surg. 70A:347, 1988.

28. Buchanan, R.A., Rigney, E.D., Williams, J.M.: Ion implantation of surgical Ti-6AI-4V for improved resistance to wear-accelerated corrosion. J. Bionned. Mater. Res. 21:355, 1987.

29. McKellop, H. and Rostlund, T.: The wear behavior of ion-implanted Ti-6AI-4V against UHMWPE. J. Biomed. Meter. Res. 24:1413, 1990.

30. Zichner, L. and Willert, H.-G.: Comparison of alumina-polyethylene and metal-polyethylene in clinical trials. Clin. Orthop. Rel. Res, 282:86, 1992.

31. Davidson, J.A.: Characteristics of metal and ceramic total hip bearing surfaces and the effect on long-term UHMWPE wear. Clin. Orthop. 285, 1992.

32. Oonishi, H., Igaki, H., Takahama, Y.: Comparisons of wear of UHMWPE sliding against metal and alumna in total hip prosthesis. Bioceramics, 1:272, 1989.

33. McKellop, H., Lu, B., Benya, P.: Friction, lubrication and wear of cobalt-chromium, alumina, and zirconia hip prostheses compared on a joint simulator. Trans. of 38th Ann. Meet. of Orthop. Res. Soc., Washington, 1992, p. 402.

34. Muller, M.E.: A new concept of acetabular fixation. In: The Hip. proc. of 13th Open Sci. Meet. of the Hip Soc. (Fitzgerald, R.H., ed.) C.V. Mosby, St. Louis, 1985, p. 269.

35. Bobyn, J.D., Dujovne, A.R., Krygier, J.J., Young, D.L.: Surface analysis of the taper junctions of retrieved and in-vitro tested modular hip prostheses. In: Biological, Material, and Mechanical Considerations ofJoint Replacement: Current Concepts and Future Direction (Morrey, B.F., ed.) Raven Press, New York, 1993.

36. Krygier, J.J., Bobyn, J.D., Dujovne, A.R., Young, D.L., Brooks, C.E.: Strength, stability, and wear analysis of titanium femoral hip prostheses tested in fatigue. Trans. of 4th World Bionnat. Congress. Berlin, 1992, p. 626.

37. Dujovne, A.R., Bobyn, J.D., Krygier, J.J., et al.: Fretting at the head/neck taper of modular hip prostheses. Trans. of 4th World Bionnat. Congress, Berlin, 1992, p. 264.

38. Bobyn, J.D., Tanzer, M., Krygier, J,J., Dujovne, A.R., Brooks, C.E.: Concerns with modular THR. Trans. of 21st Open Meet. of the Hip Society, San Francisco, 1993.

39. Collier, J.P., Surprenant, V.A., Jensen, R.E., Mayor, M.B.: Corrosion at the interface of cobalt-alloy heads on titanium-alloy stems. Clin. Orthop. 271:305, 1991.

40. Collier, J.P., Surprenant, V.A., Jensen, R.E., Mayor, M.B., Surprenant, H.: Corrosion between the components of modular femoral hip prostheses. J. Bone Joint Surg. 74B:511, 1992.

41. Mathiesen, E.B., Lindgren, J.U., Blomgren, G.G.A., Reinholt, F.P.: Corrosion of modular hip prostheses. J. Bone Joint Surg. 7313:259, 1991.

42. Gilbert, J.L., Buckley, C.A., Jacobs, J.J., et al.: Mechanically assisted corrosive attack in the Morse taper of modular hip prostheses. Trans. of 4th World Biomat. Congress, Berlin, 1992, P. 267.

43. Brown, S.A., Flemming, C.A.C., Kawalec, J.S. et al.: Fretting accelerated crevice corrosion of modular hips. Trans. of Soc. for Biomat. Implant Retrieval Symp. 1992, p. 59.

44. Collier, J.P.: Personal communication.

45. Crowninshield, R., Price, H., Parr, J., Gilbertson, L., Lower, J., Shetty, R.: Hardness, abrasion resistance, and particulate release from metallic implant surfaces. Trans. of 37th Ann. Meet. of Orthop. Res. Soc., Anaheim, 1991, p. 91.

46. McTighe, T., Hastings, R., Vaughn, B.K., Vise, G.T.: Surface finishes for titanium cementless stems. Poster Exhibit. 60th Ann. Meet. of AAOS, San Francisco, 1993.

47. Kasemo, B., Lausmas, J.: Bionnaterial and implant surfaces: on the role of cleanliness, contamination, and preparation procedures. J. Biomed. Meter. Res. Appl. Biomater. 22 (Suppl. A2):145, 1988.

48. Ricci, J.L., Kummer, F.J., Alexander, H., Casar, R.S.: Embedded particulate contaminants in textured metal implant surfaces. J. Applied Biomat., 3:225, 1992.

49. Buchert, P.K., Vaughn, B.K., Mallory, T.H., et al.: Excessive metal release due to loosening and fretting of sintered particles on porous-coated hip prostheses. Report of two cases. J. Bone Joint Surg. 6BA:606, 1986.

50. Bobyn, J.D. and Miller, J.E.: Features of biologically fixed devices. In: Joint Replacement Arthroplasty (Morrey, B.F., ed.) Chruchill Livingstone, New York, 1991, p. 61.

51. Callaghan, J.J., Dysart, S.H., Savory, C.G.: The uncemented porous-coated anatomic total hip prosthesis. Two-year results of a prospective consecutive series. J. Bone Joint Surg. 70A:337, 1988.

52. Bloebaum, R.D. and Dupont, J.A.: Osteolysis from a press-fit hydroxyapatite coated implant: a case study. J. Arthroplasty (Suppl.) April, 1993.

53. Campbell, P., McKellop, H., Park, S.H., Malcom, A.: Evidence of abrasive wear by particles from a hydroxyapatite coated hip prosthesis. Trans. of 39th Ann. Meet. of Orthop. Res. Soc., San Francisco, 1993.

54. Dumbleton, J.H.: Wear and prosthetic joints. In: Joint Replacement Arthroplasty (Morrey, B.F., ed.) Churchill Livingstone, New York, 1991, p. 47.

55. Tanzer, M., Maloney, W.J., Jasty, M., Harris, W.H.: The progression of femoral cortical osteolysis in association with total hip arthroplasty without cement. J. Bone Joint Surg. 74A:404, 1992.

56. Howie, D.W., Vernon-Roberts, B., Oakeshott, R., Manthey, B.: A rat model of resorption of bone at the cement-bone interface in the presence of polyethylene wear particles. J. Bone Joint Surg . 70A:257, 1988.

57. Bolbyn, J.D., Aribindi, R., Mortimer, E., Tanzer, M.: The effect of noncemented implant surface geometry on polyethylene debris migration and peri-implant histogenesis. Trans. of 27th Ann. Meet. of Canadian Orthop. Res. Soc., Montreal, 1993.

58. Hill, G.E.: HGP press-fit at five years. Trans. of 22nd Ann. Hip Course (Harris, W.H., dir.), Boston, 1992.