

Chapter 2

Bearing Surfaces for Joint Replacement: New Materials or New Problems

Stuart Goodman

Total joint replacement (TJR) is one of the greatest technological advances in all of surgery. Hip, knee, and shoulder replacements, as well as reconstruction of smaller joints with artificial materials are currently performed worldwide. These procedures decrease pain and improve function in a cost-effective manner, and thereby improve the quality of life for millions of patients with end-stage arthritis.

Initially, most modern TJRs consisted of a bearing couple composed of a metallic alloy that articulated with conventional medical grade polyethylene [1]. This combination of materials functioned satisfactorily for many years in low demand, elderly patients for whom TJRs were originally designed. However, as joint replacement procedures were extended to younger more active higher-demand patients, wear of the polyethylene and the subsequent adverse biological reaction to wear byproducts became a serious concern [2].

Wear of the bearing materials of a TJR is a function of use, not time in vivo [3]. Higher-demand patients engage in greater numbers of gait cycles per day, and often participate in higher-impact sporting activities that increase wear [4]. Polyethylene wear particles generated at the articulation are pumped and distributed throughout the “effective joint space”, producing in some cases chronic synovitis, progressive bone loss (periprosthetic osteolysis), implant loosening and pathologic fracture [5]. Subsequent surgical reconstruction of loose TJRs with extensive periprosthetic bone loss is challenging; these surgical procedures are long and costly and have a higher complication rate and a poorer outcome compared to primary procedures [2]. These facts have stimulated intense research to improve the tribological characteristics of current materials, as well as develop newer more wear resistant bearing couples that potentially could last a lifetime [6]. Although this goal has not yet been realized, significant improvements in implant materials have been achieved in the last two decades. At the same time, unexpected obstacles have surfaced which have led, in some cases, to earlier revision surgery than with conventional materials.

S. Goodman (✉)

Departments of Orthopaedic Surgery and Bioengineering,
Stanford University, Stanford, USA
e-mail: goodbone@stanford.edu

The Inflammatory Reaction to Wear Debris

Wear particles are generated at all artificial joint articulations. These particles are largely in the micron and submicron range, with metallic particles being amongst the smallest [7–9]. Wear particles of polymethylmethacrylate (PMMA), polyethylene (PE) and ceramics evoke a nonspecific, non-antigenic chronic inflammatory and foreign body reaction [10]. The cellular components of this reaction commonly include the monocyte/macrophage cell lineage (macrophages, foreign body giant cells and osteoclasts), activated fibroblasts, with occasional polymorphonuclear leukocytes (PMNs) and lymphocytes [11–13]. Larger wear particles of metals such as stainless steel, cobalt chrome alloy and titanium alloy incite a similar chronic inflammatory reaction; however, recent evidence has demonstrated that metal byproducts may also produce a Type IV allergic reaction in some situations (see below) [14].

Macrophages and other cells phagocytize particles less than about 10 microns in diameter, as part of the innate immune response to foreign materials [2, 7, 8, 13, 15]. The wear debris is non-digestible and activates the cells to produce and release pro-inflammatory cytokines, chemokines, prostanoids, reactive oxygen species and other factors that, in the end, stimulate osteoclasts to degrade bone [15–17]. At the same time, homeostatic mechanisms are initiated that induce local bone formation [13, 18]. However, with ongoing production of wear debris, the balance between bone destruction and bone formation favours the former, leading to periprosthetic osteolysis, and potentially, implant loosening and fracture [18, 19]. Because of the cyclic nature of walking which induces high intra-articular pressures, the particles, cells and inflammatory factors are pumped and distributed around the prosthesis and insinuate into the adjacent cancellous bone along the bone–implant interface [20]. From this pumping and distribution, osteolysis can be seen adjacent to and remotely from the prosthesis bearing couple. Increased local fluid pressure also induces bone destruction [21]. The cells that phagocytize particles eventually die, liberating the particulate debris that continues to perpetuate the inflammatory cycle. Furthermore, recent *in vivo* studies have shown that wear particles induce a systemic biological response, rather than only a local response [22, 23]. Through the action of chemotactic cytokines or chemokines, inflammatory and reparative cells are mobilized to the site of particle generation to participate in the inflammatory cascade, attempt to contain this adverse reaction, and restore normal tissue architecture [22–27].

Although biological approaches are currently being explored to improve the osseointegration of implants (to provide a more robust bone–implant interface) and to mitigate wear particle induced inflammation, perhaps a more direct approach is to develop more wear resistant materials. In essence this amounts providing bearing couples that generate fewer wear particles, with conceivably more benign biological physico-chemical properties, which will not perturb local tissue homeostasis. This goal would aim to provide a “permanent” joint replacement that would allow full activities (including impact loading) for the duration of the patient’s life.

New Polyethylenes

As stated above, metal-on-conventional ultra high molecular weight polyethylene has been the traditional bearing surface for many decades. This material has performed well in the very elderly, more sedentary population. However, in more active younger individuals with greater numbers of gait cycles per year, more wear particles are produced [3]. In general, polyethylene linear wear rates of less than 0.1 mm per year produce little osteolysis compared with higher wear rates [28]. Increased wear is produced by chain scission and oxidation of the linearly arranged polyethylene molecules. Recent attempts to improve the wear characteristics of polyethylene have included: altering the crystallinity of polyethylene, irradiating and packaging the product in an inert (non-oxygen containing) environment, irradiating and heating (above the melting point) and/or annealing the polyethylene to induce a more highly cross-linked end product that contains fewer free radicals, sequential irradiating and annealing protocols below the melting point of polyethylene, and adding surface coatings or free radical scavengers [29–31]. Although most of these new processes have shown highly encouraging early and intermediate clinical results after more than one decade of use, no long-term (20 + year) clinical outcomes have been reported [32]. Cross-linked polyethylene (XLPE) has less optimal mechanical properties (including toughness, ductility and resistance to fatigue) compared to conventional polyethylene [33–35]. Issues related to the use of larger femoral heads (to prevent dislocation) that articulate with thinner polyethylene acetabular liners have lead to reports of polyethylene rim fractures, necessitating revision surgery [36, 37]. This has been seen more commonly in implants with suboptimal positioning (for example, an excessively abducted or anteverted acetabular cup). Although in vitro studies have suggested potentially higher adverse biological reactions to wear particles from cross-linked polyethylene, compared to conventional polyethylene, the numbers of particles generated are decreased with the XLPE material as to almost negate this point [38–40]. However, not all XLPEs are exactly alike. The irradiation protocols, processing, packaging and other variables are different for each manufacturer [32]. Patients with XLPE components are still not encouraged to engage in impact loading activities that could damage the articular surface.

Ceramic Bearings

The use of ceramic-on-ceramic (CoC) bearings was popularized in France, Japan and Korea, but has been less popular in the United States. These bearings are biocompatible, display low friction, high-wear resistance and produce few wear particles with normal usage [41]. Intermediate term series have reported very encouraging results [42, 43]. The problem of catastrophic fracture of ceramic femoral heads in total hip replacement has largely been avoided with newer ceramics with smaller grain sizes. However, some new unanticipated problems have come to light with CoC bearings [44, 45]. Modular acetabular cups may be difficult to assemble, may seat

incompletely, or dissociate from their metal backing. Third body interposition (with soft tissue, bone spicules, etc.) between modular components may be an issue in assembly. Chipping of the liner may also occur at surgery or with later impingement. Edge loading with striped wear may take place due to increased range of motion and cyclic micro-separation during gait, especially if the components are in suboptimal position [41, 44]. Troublesome and embarrassing audible squeaking has been noted with some implant designs. In addition, these implants are generally more expensive than metal-on-polyethylene (MoP) articulations. Nonetheless, CoC bearings facilitate the use of larger femoral heads and generally allow more normal activities, even high-impact sports according to surgeons who utilize them [43].

Metal-on-Metal (MoM) Bearings

MoM bearings were recently re-introduced for several reasons, including the high wear rates and high incidence of osteolysis with metal-on-conventional polyethylene bearings in younger patients, and for resurfacing arthroplasty [46]. MoM bearings depend on a high level of congruence of the articulating metallic surfaces to encourage fluid film lubrication [47]. This results in extremely low wear rates [41, 48]. The head sizes can be larger than with a MoP bearing, increasing the range of motion and overall stability of the joint. These points lead to a resurgence of MoM bearing surfaces, which at one point constituted about 25 % or more of the hip replacement market in the USA. The early and mid-term results for some MoM total hip and resurfacing implants were very encouraging [49]. However, the enthusiasm for this bearing couple has waned somewhat because of issues related to pain and adverse tissue reactions with some implants [48]. Indeed several suboptimal implant designs with unacceptably high failure rates have been withdrawn from the marketplace [50, 51].

In general, patients with MoM total hip replacements have a higher incidence of adverse tissue reactions compared with those with MoP or CoC bearings. Some MoM failures are the result of a type IV hypersensitivity reaction to metal particles and their byproducts [41, 47]. The clinical presentation may vary from a diffusely painful joint with chronic synovitis and no other abnormal radiographic features to loosening, osteolysis or pseudotumor formation. Registry data from several countries have shown a higher revision rate for MoM bearing THRs [48, 52, 53]. Larger head sizes (> 28 mm) appear to increase these adverse events compared to smaller head sizes.

Willert and colleagues published a seminal study on adverse tissue reactions to MoM bearings and implicated a hypersensitivity reaction to metallic byproducts [14]. They noted prominent perivascular lymphocytic cuffing in the periprosthetic tissues and implicated immune processes for the adverse clinical outcomes in some patients. Patients with high wear rates of MoM hip implants, especially those with suboptimal alignment leading to edge loading, may have increased metal ion levels of cobalt and chromium in the blood. In vitro and in vivo studies have demonstrated that metal

particulates and their byproducts may be associated with cytotoxicity, DNA damage (DNA-strand breaks, inhibition of DNA repair, chromosomal aberrations, etc.), metal hypersensitivity reactions and pseudotumors [47, 54]. Metal particles are about 30–200 nm in size; ionic complexes may form due to corrosion and other processes that degrade the alloys. The numbers of these smaller particles are often 2–3 orders of magnitude greater than with MoP articulations. These small metallic particles are small enough to cross the placenta. Although some hematopoietic abnormalities have been noted with MoM bearings, the incidence of different cancers in patients with MoM bearing surfaces does not appear to be higher compared to conventional MoP bearing surfaces [55].

In the last several years, the number of new MoM resurfacing arthroplasties has decreased dramatically, especially in younger women with smaller implant sizes [56]. These higher-risk patients are particularly susceptible to adverse immunological events due to wear byproducts from MoM implants [47]. Resurfacing arthroplasty is reported to have a much higher success rate in younger males with good bone stock and little deformity.

Other Bearing Couples

Other novel, so-called “hard-on-hard” bearing couples (such as ceramic-on-metal etc.) have recently been introduced to avoid the metallic byproduct issue altogether [46]. Longer-term studies are needed to determine their importance as a practical articulation for hip replacement.

Summary

As the general population continues to age, and high demands are placed on joint replacements to function for prolonged periods of time, issues related to implant materials become more prominent. Thorough preclinical assessment of newly introduced materials must be rigorous to avoid some of the pitfalls noted during the last one to two decades. Although advances have been made, the long-lasting, high-performance joint replacement that will function normally *in vivo* is still elusive.

This work was supported in part by National Institute of Health (NIH) grants 2R01 AR055650-05 and 1R01 AR063717-01.

References

1. Charnley J (1979) Low friction arthroplasty of the hip. Springer, New York
2. Goodman SB, Gomez Barrena E, Takagi M, Kontinen YT (2009) Biocompatibility of total joint replacements: a review. *J Biomed Mater Res A* 90(2):603–618

3. Schmalzried TP, Shepherd EF, Dorey FJ, Jackson WO, dela Rosa M, Fa'vae F et al (2000) The John Charnley award. Wear is a function of use, not time. *Clin Orthop Relat Res* 2000(381):36–46
4. Marshall A, Ries MD, Paprosky W (2008) How prevalent are implant wear and osteolysis, and how has the scope of osteolysis changed since 2000? *J Am Acad Orthop Surg* 16(Suppl 1):S1–S6
5. Schmalzried TP, Kwong LM, Jasty M, Sedlacek RC, Haire TC, O'Connor DO et al (1992) The mechanism of loosening of cemented acetabular components in total hip arthroplasty. Analysis of specimens retrieved at autopsy. *Clin Orthop Relat Res* 1992(274):60–78
6. Campbell P, Shen FW, McKellop H (2004) Biologic and tribologic considerations of alternative bearing surfaces. *Clin Orthop Relat Res* 2004(418):98–111
7. Hallab NJ, Jacobs JJ (2009) Biologic effects of implant debris. *Bull NYU Hosp Jt Dis* 67(2):182–188
8. Ingham E, Fisher J (2002) Biological reactions to wear debris in total joint replacement. *Proc Inst Mech Eng H* 214(1):21–37
9. Shanbhag AS, Jacobs JJ, Glant TT, Gilbert JL, Black J, Galante JO (1994) Composition and morphology of wear debris in failed uncemented total hip replacement. *J Bone Joint Surg Br* 76(1):60–67
10. Meneghini RM, Hallab NJ, Jacobs JJ (2005) The biology of alternative bearing surfaces in total joint arthroplasty. *Instr Course Lect* 54:481–493
11. Holt G, Murnaghan C, Reilly J, Meek RM (2007) The biology of aseptic osteolysis. *Clin Orthop Relat Res* 460:240–252
12. Jacobs JJ, Roebuck KA, Archibeck M, Hallab NJ, Glant TT (2001) Osteolysis: basic science. *Clin Orthop Relat Res* 2001(393):71–77
13. Revell PA (2008) The combined role of wear particles, macrophages and lymphocytes in the loosening of total joint prostheses. *J R Soc Interface* 5(28):1263–1278
14. Willert HG, Buchhorn GH, Fayyazi A, Flury R, Windler M, Koster G et al (2005) Metal-on-metal bearings and hypersensitivity in patients with artificial hip joints. A clinical and histomorphological study. *J Bone Joint Surg Am* 87(1):28–36
15. Purdue PE, Koulouvaris P, Potter HG, Nestor BJ, Sculco TP (2007) The cellular and molecular biology of periprosthetic osteolysis. *Clin Orthop Relat Res* 454:251–261
16. Tuan RS, Lee FY, Konttinen Y, Wilkinson JM, Smith RL (2008) What are the local and systemic biologic reactions and mediators to wear debris, and what host factors determine or modulate the biologic response to wear particles? *J Am Acad Orthop Surg* 16(Suppl 1):S33–38
17. Goodman SB, Huie P, Song Y, Schurman D, Maloney W, Woolson S et al (1998) Cellular profile and cytokine production at prosthetic interfaces. Study of tissues retrieved from revised hip and knee replacements. *J Bone Joint Surg Br* 80(3):531–539
18. Kadoya Y, Revell PA, al-Saffar N, Kobayashi A, Scott G, Freeman MA (1996) Bone formation and bone resorption in failed total joint arthroplasties: histomorphometric analysis with histochemical and immunohistochemical technique. *J Orthop Res* 14(3):473–482
19. Willert HG (1977) Reactions of the articular capsule to wear products of artificial joint prostheses. *J Biomed Mater Res* 11(2):157–164
20. Aspenberg P, Van der Vis H (1998) Migration, particles, and fluid pressure. A discussion of causes of prosthetic loosening. *Clin Orthop Relat Res* 1998(352):75–80
21. Aspenberg P, Vis H van der (1998) Fluid pressure may cause periprosthetic osteolysis. Particles are not the only thing. *Acta Orthop Scand* 69(1):1–4
22. Ren PG, Irani A, Huang Z, Ma T, Biswal S, Goodman SB (2011) Continuous infusion of UHMWPE particles induces increased bone macrophages and osteolysis. *Clin Orthop Relat Res* 469(1):113–122
23. Fritton K, Ren PG, Gibon E, Rao AJ, Ma T, Biswal S et al (2012) Exogenous MC3T3 pre-osteoblasts migrate systemically and mitigate the adverse effects of wear particles. *Tissue Eng Part A* 18(23–24):2559–2567
24. Ren W, Markel DC, Schwendener R, Ding Y, Wu B, Wooley PH (2008) Macrophage depletion diminishes implant-wear-induced inflammatory osteolysis in a mouse model. *J Biomed Mater Res A* 85(4):1043–1051

25. Jiranek WA, Machado M, Jasty M, Jevsevar D, Wolfe HJ, Goldring SR et al (1993) Production of cytokines around loosened cemented acetabular components. Analysis with immunohistochemical techniques and in situ hybridization. *J Bone Joint Surg Am* 75(6):863–879
26. Goodman SB (2007) Wear particles, periprosthetic osteolysis and the immune system. *BioMaterials* 28(34):5044–5048
27. Gibon E, Batke B, Jawad MU, Fritton K, Rao A, Yao Z et al (2012) MC3T3-E1 osteoprogenitor cells systemically migrate to a bone defect and enhance bone healing. *Tissue Eng Part A* 18(9–10):968–973
28. Dumbleton JH, Manley MT, Edidin AA (2002) A literature review of the association between wear rate and osteolysis in total hip arthroplasty. *J Arthroplasty* 17(5):649–661
29. Kurtz SM, Gawel HA, Patel JD (2011) History and systematic review of wear and osteolysis outcomes for first-generation highly crosslinked polyethylene. *Clin Orthop Relat Res* 469(8):2262–2277
30. Oral E, Muratoglu OK (2011) Vitamin E diffused, highly crosslinked UHMWPE: a review. *Int Orthop* 35(2):215–223
31. Gordon AC, D’Lima DD, Colwell CW Jr (2006) Highly cross-linked polyethylene in total hip arthroplasty. *J Am Acad Orthop Surg* 14(9):511–523
32. Jacobs CA, Christensen CP, Greenwald AS, McKellop H (2007) Clinical performance of highly cross-linked polyethylenes in total hip arthroplasty. *J Bone Joint Surg Am* 89(12):2779–2286
33. Atwood SA, Van Citters DW, Patten EW, Furmanski J, Ries MD, Pruitt LA (2011) Tradeoffs amongst fatigue, wear, and oxidation resistance of cross-linked ultra-high molecular weight polyethylene. *J Mech Behav Biomed Mater* 4(7):1033–1045
34. Schroder DT, Kelly NH, Wright TM, Parks ML (2011) Retrieved highly crosslinked UHMWPE acetabular liners have similar wear damage as conventional UHMWPE. *Clin Orthop Relat Res* 469(2):387–394
35. Rimnac C, Pruitt L (2008) How do material properties influence wear and fracture mechanisms? *J Am Acad Orthop Surg* 16(Suppl 1):S94–S100
36. Furmanski J, Anderson M, Bal S, Greenwald AS, Halley D, Penenberg B et al (2009) Clinical fracture of cross-linked UHMWPE acetabular liners. *BioMaterials* 30(29):5572–5582
37. Waewsawangwong W, Goodman SB (2012) Unexpected failure of highly cross-linked polyethylene acetabular liner. *J Arthroplasty* 27(2):323 e1–e4
38. Fisher J, McEwen HM, Tipper JL, Galvin AL, Ingram J, Kamali A et al (2004) Wear, debris, and biologic activity of cross-linked polyethylene in the knee: benefits and potential concerns. *Clin Orthop Relat Res* 2004(428):114–119
39. Illgen RL 2nd, Bauer LM, Hotujec BT, Kolpin SE, Bakhtiar A, Forsythe TM (2009) Highly crosslinked vs conventional polyethylene particles: relative in vivo inflammatory response. *J Arthroplasty* 24(1):117–124
40. Illgen RL 2nd, Forsythe TM, Pike JW, Laurent MP, Blanchard CR (2008) Highly crosslinked vs conventional polyethylene particles—an in vitro comparison of biologic activities. *J Arthroplasty* 23(5):721–731
41. Zywiell MG, Sayeed SA, Johnson AJ, Schmalzried TP, Mont MA (2011) 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
42. D’Antonio JA, Capello WN, Naughton M (2012) Ceramic bearings for total hip arthroplasty have high survivorship at 10 years. *Clin Orthop Relat Res* 470(2):373–381
43. Hannouche D, Zaoui A, Zadegan F, Sedel L, Nizard R (2011) Thirty years of experience with alumina-on-alumina bearings in total hip arthroplasty. *Int Orthop* 35(2):207–213
44. Jeffers JR, Walter WL (2012) Ceramic-on-ceramic bearings in hip arthroplasty: state of the art and the future. *J Bone Joint Surg Br* 94(6):735–745
45. Barrack RL, Burak C, Skinner HB (2004) Concerns about ceramics in THA. *Clin Orthop Relat Res* 2004(429):73–79
46. Cigada A, Cotogno G, Chiesa R (2011) The ceramic-on-metal coupling in total hip replacements for young patients: a review study. *J Appl Biomater Biomech* 9(1):2–10

47. Gill HS, Grammatopoulos G, Adshead S, Tsialogiannis E, Tsiridis E (2012) Molecular and immune toxicity of CoCr nanoparticles in MoM hip arthroplasty. *Trends Mol Med* 18(3):145–155
48. Bozic KJ, Browne J, Dangles CJ, Manner PA, Yates AJ Jr, Weber KL et al (2012) Modern metal-on-metal hip implants. *J Am Acad Orthop Surg* 20(6):402–406
49. Shetty V, Shitole B, Shetty G, Thakur H, Bhandari M (2011) Optimal bearing surfaces for total hip replacement in the young patient: a meta-analysis. *Int Orthop* 35(9):1281–1287
50. Steiger RN de, Hang JR, Miller LN, Graves SE, Davidson DC (2011) Five-year results of the ASR XL acetabular system and the ASR hip resurfacing system: an analysis from the Australian orthopaedic association national joint replacement registry. *J Bone Joint Surg Am* 93(24):2287–2293
51. Langton DJ, Jameson SS, Joyce TJ, Gandhi JN, Sidaginamale R, Mereddy P et al (2011) Accelerating failure rate of the ASR total hip replacement. *J Bone Joint Surg Br* 93(8):1011–1106
52. Smith AJ, Dieppe P, Vernon K, Porter M, Blom AW (2012) Failure rates of stemmed metal-on-metal hip replacements: analysis of data from the National Joint Registry of England and Wales. *Lancet* 379(9822):1199–1204
53. Graves SE, Rothwell A, Tucker K, Jacobs JJ, Sedrakyan A (2011) A multinational assessment of metal-on-metal bearings in hip replacement. *J Bone Joint Surg Am* 93(Suppl 3):43–47
54. Mabilieu G, Kwon YM, Pandit H, Murray DW, Sabokbar A (2008) Metal-on-metal hip resurfacing arthroplasty: a review of periprosthetic biological reactions. *Acta Orthop* 79(6):734–747
55. Makela KT, Visuri T, Pulkkinen P, Eskelinen A, Remes V, Virolainen P et al (2012) Risk of cancer with metal-on-metal hip replacements: population based study. *BMJ* 345:e4646
56. Macpherson GJ, Breusch SJ (2011) Metal-on-metal hip resurfacing: a critical review. *Arch Orthop Trauma Surg* 131(1):101–110

Metal-on-Metal Bearings

A Clinical Practicum

Jones, L.C.; Haggard, W.O.; Greenwald, A.S. (Eds.)

2014, X, 200 p. 46 illus., 26 illus. in color., Hardcover

ISBN: 978-1-4614-8998-6