Chapter 2
Bearing Surfaces for Joint Replacement: New Materials or New Problems

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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.

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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.

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