Review

Ultra High Molecular Weight Polyethylene Wear in Total Hip Arthroplasty

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Increased longevity of total hip arthroplasty (THA) and its use in younger active patients has led to a greater incidence of clinical and radiographic apparent ultra high molecular weight polyethylene (UHMWPE) wear. In generic terms, wear is defined as the progressive loss of substance from the operating surface of a body occurring as a result of relative motion of the surface. With respect to THA, this wear is best quantitated through radiographic means as linear wear. Linear wear is the straight line distance the femoral head travels into the UHMWPE cup or insert and is expressed as millimeters per year. Several radiographic reviews of long-term performance of THAs have reported average rates of linear wear between 0.07 and 0.19 mm/year. 

Measured linear wear is the sum of true linear wear and creep. The magnitude of the contribution of creep, ie, time-dependent strain caused by stress to linear wear, is not known precisely. Rose et al. attempted to determine the contribution of creep to linear wear. They collected and weighed all of the wear particles generated by individual prostheses in a hip stimulator and found the weight of the generated wear particles accounted for only 1%-30% of the dimensional changes of the UHMWPE. The remainder of the dimensional changes were ascribed to creep. Thus, it is clear that creep accounts for a significant portion of measured linear wear.

MECHANISMS OF WEAR

The mechanisms of wear in THA are abrasion, adhesion, and fatigue. Abrasive wear is the removal of a material from the operating surface of a body by hard asperities on the counter-surface (two-body wear) or by hard particles between the surfaces (three-body wear). Asperities are microscopic incongruities on the surface of the prosthesis.

In two-body wear, these asperities can remove material from the softer UHMWPE inserts. Three-body wear is most frequently caused by particles of polymethylmethacrylate that interpose themselves between the surfaces. They can grind off large quantities of UHMWPE from the acetabular components. Many authors believe three-body wear causes the accelerated wear occasionally observed in THA.

Adhesive wear is defined as the transfer of material from one surface to another due to a process of solid-phase welding. This occurs when two asperities contact each other. Large pressures are generated over this small contact point and can be strong enough to form covalent bonds between the surfaces. The majority of these bonds are broken when the surfaces separate. However, approximately 10% of these bonds are strong enough to cause a fracture in the UHMWPE. When these covalent bonds eventually break, a wear particle is formed.

Fatigue wear is defined as the
removal of material from the operating surface of a body as a result of cyclic stress variations. These cyclic stresses are termed Van Mises stresses and are concentrated 1-2 mm beneath the bearing surface of the UHMWPE. This results in subsurface cracks that either propagate parallel to the surface and cause delamination or propagate to the surface and result in pitting. Unlike abrasive and adhesive wear, fatigue wear increases with time. Fatigue wear is most prevalent in total knee arthroplasty and plays a lesser role than abrasive or adhesive wear in THA.

Wear between two bodies in motion and in contact is inevitable. Thus, wear will always occur between the bearing surfaces in THA. The magnitude of this wear is dependent on certain characteristics of the prostheses and the patients in whom the prostheses are implanted. The size of the prosthetic head, the materials from which the prostheses are composed, the thickness of the UHMWPE cup or liner, and the weight and activity of the patient all act in concert to determine the wear rate of each prosthesis.

Livermore et al. retrospectively reviewed the volumetric and linear wear rates of 395 hips with follow-up of at least 9.5 years. Their cohort was divided into three groups according to head sizes: 32-mm, 28-mm, and 22-mm groups. These three groups had similar demographic characteristics and underwent follow-up for equal amounts of time. The greatest rate of linear wear was reported for the 22-mm head group while the 32-mm head group demonstrated the greatest amount of volumetric wear. The 28-mm group fell between both groups in both volumetric and linear wear.

Gold and Walker, using a hip joint simulator, reported decreased wear for 28-mm heads compared to 32-mm heads. In a finite element analysis, Hoelzessel et al. estimated the stresses in metal-backed UHMWPE liners that were articulated with femoral heads of varying diameters. Head sizes were modeled from 20-40 mm in 2-mm increments. The 26-mm heads caused the least amount of stress in the UHMWPE liner. In addition, both Morrey and L'Intypré and Ritter et al. have reported a positive correlation between aseptic loosening of prosthesis and the use of 32-mm heads. Thus, most surgeons recommend the use of either 26- or 28-mm heads.

**Patient Characteristics and Wear**

During single limb stance, the hip is subjected to stresses at least four times body weight. These stresses increase during activities such as running, jumping, and stair climbing. Thus, one would reason that increasing patient weight and activity would lead to increasing rates of UHMWPE wear. However, several studies have failed to demonstrate a correlation between patient weight or activity level with wear. Livermore et al. found a correlation between volumetric, but not linear, wear with patient weight.

The lack of correlation in most studies between patient characteristics and wear is surprising. An explanation for this is that other factors such as femoral head size and the quality and thickness of the UHMWPE affect the wear rate more than patient characteristics and thus mask the affect that these characteristics have on wear.

**Ceramic Heads**

Extensive experience with ceramic heads in THA has been accumulated in Europe. However, only recently has the use of ceramic femoral heads become popular in North America.

Theoretical advantages of ceramics as a bearing surface include increased wettability, decreased coefficient of friction, and decreased in vitro wear. Wettability is a measure of the hydrophilicity of a material. The more wettable a material is, the more strongly it bonds with water. This bonding results in the formation of a lubricating film between the contacting surfaces which reduces friction. In addition, ceramics can be polished to form a better surface than metals, thus decreasing surface incongruities or asperities. In vitro wear tests comparing ceramic heads and metallic heads articulating with UHMWPE liners performed on hip simulators have reported decreased wear in the ceramic-UHMWPE construct.

Because ceramics are extremely brittle and demonstrate poor resistance to crack propagation, they are prone to fracture. In a review of Miteklinier prosthesis, Winter et al. reported an 8% fracture rate of ceramic heads. Recent designs of ceramic heads have eliminated the risk of fracture. However, because of design constraints in the ceramic Morse taper mechanism, these heads are available only in mid-range neck lengths.

The cost of ceramic heads usually is two to three times that of metallic heads. In this era of cost containment, the increased cost must be considered a disadvantage to their use. Because of their superior wear characteristics coupled with increased cost, most surgeons recommend the use of ceramic heads only in young patients.

**Polyethylene Thickness and Wear**

The wear characteristics of UHMWPE are affected by its thickness. In classic studies, Bartel et al. demonstrated peak contact stresses experienced by the UHMWPE varied inversely with its thickness. Through the use of finite element analysis, they predicted the contact stress in a metal-backed UHMWPE insert <6 mm would exceed the fatigue strength of the UHMMPWE. Thus, they recommended against the use of UHMWPE inserts <6 mm thick in a load-bearing area.

The 6-mm limit easily is exceeded by the UHMWPE thickness in classic Charnley all-UHMWPE cups with an internal diameter of 22-25 mm. Unfortunately, the addition of metal backing to the cups in combination with the use of larger head sizes resulted in UHMWPE liners of less than the recommended thickness.

Fehring et al. illustrated this point
in a cross-sectional analysis of five commonly used acetabular components. When 32-mm heads were combined with 52-mm metal-backed cups, two of five component designs tested contained UHMWPE < 6 mm in the load-bearing area. When 64-mm outside diameter cups were used, all of the liners were > 6 mm thick in the load-bearing area.

No cup with an outer diameter of 52 mm contained 6 mm of UHMWPE thickness at the periphery of the cup regardless of the head size tested. One cup design contained only 1.8 mm of UHMWPE at its locking mechanism when a 32-mm inner diameter/52-mm outer diameter construct was examined. The periphery of a acetabular cup is not designed to be load bearing when the cup is implanted anatomically. Occasionally, to gain coverage or as the result of a technical error, cups are vertically placed. This positioning results in load bearing on the thin peripheral UHMWPE, which can lead to accelerated wear.

Deficiencies in the locking mechanisms of certain other modular cup designs allow motion to occur between the liner and the metal backing. In addition, the undersurfaces of these metal backed cups have a rough finish. The motion of the liner against the roughened metallic results in UHMWPE wear. In response to this, most modern modular cup designs incorporate a metal backing with a polished inner surface and a rigid locking mechanism. These modifications minimize motion and wear between the cup and liner.

**FLAWS IN MANUFACTURING PROCESS**

Flaws inherent in the manufacturing process of UHMWPE can lead to accelerated wear regardless of prosthetic design or patient characteristics. Large batch-to-batch variations in yield strength, tensile strength, creep resistance, and molecular weight of UHMWPE have been reported by Collier et al. In addition, they discovered internal flaws in never-implanted UHMWPE components, which they termed "voids." Analysis of these voids revealed they consisted of calcium and chloride. These materials are used as catalysts in the polymerization of UHMWPE. The presence of these voids decreases the strength and wear resistance of the UHMWPE.

Rose et al analyzed the surface of never-implanted UHMWPE components with a scanning electron microscope. They discovered that incomplete polymerization of the particulate UHMWPE occurred, resulting in fusion defects on the bearing surface. These fusion defects sometimes coalesce and cause relatively large particles of UHMWPE to detach from the surface of the components. Both Rose et al and Collier et al hypothesize these inherent defects in the UHMWPE cause accelerated wear of components in vivo.

Recently, investigators found that polyethylene components oxidized both prior to and after implantation. This oxidation occurs as a result of the sterilization process. When polyethylene components are sterilized by gamma irradiation in an oxygen containing environment, chain scissions of the polymer occur. These scissions allow carbonyl groups to form in the hydrocarbon chain. This, combined with the formation of free radicals, initiates the process of oxidation.

Collier et al demonstrated that it takes at least 2 years before visible signs of this process manifest itself. They further demonstrated that the point of maximal oxidation is located 1-2 mm beneath the surface of the polyethylene components. Sutula and Collier found that this oxidized zone contained polyethylene, which demonstrated inferior mechanical and wear characteristics. The polyethylene on this zone displayed decreased resistance to crack propagation and fatigue wear. Kurtz et al reported that at 42 months postirradiation, this subsurface oxidized area had a 15% decrease in strain and a similar increase in stress. Both of these are indicative of inferior wear resistance. Most importantly, the subsurface location of the area of oxidation corresponds to precisely where Von Mises stress forces are concentrated. This leads to high rates of fatigue wear, crack propagation, and delamination of the polyethylene component at this location.

Investigators have developed new methods of sterilization that do not cause oxidation. These methods include gamma irradiation in an oxygen-free environment as well as ethylene oxide sterilization. Both Collier et al and Bargmann et al demonstrated these new sterilization methods greatly reduce the oxidation of the components. Awareness of the progressive nature of component oxidation has forced manufacturers to remove older air irradiated components from use. Most new components are now also either vacuum wrapped or wrapped in inert gas to prevent oxidation while they are stored on the shelf awaiting implantation. In this way, manufacturers are attempting to extend the "shelf life" of the components.

Another way in which the wear characteristics of polyethylene can be improved is by cross-linking. Cross-linked polyethylene demonstrates superior wear characteristics and has many industrial uses. Polyethylene can be cross-linked by several proprietary methods that involve irradiating and then remelting the components. Eddin et al demonstrated decreased abrasive wear of acetabular components made of cross-linked polyethylene in an in vitro model. McKellop et al also reported that cross-linked polyethylene demonstrated increased resistance to oxidation and improved wear characteristics in a hip joint simulator. Thus, cross-linked polyethylene appears to be a promising development. However, more long-term studies must be performed prior to its widespread use as a bearing surface.

**CLINICAL EFFECTS OF WEAR**

Wear of UHMWPE components can adversely affect the clinical performance of THAs. These adverse effects are manifested through osteolysis, dislocation of the hip, and fracture of the
UHMWPE liners or cups. Particulate UHMWPE elicits a vigorous inflammatory response by the host. This response is mediated by the macrophage.\textsuperscript{33,34} The response is propagated by the secretion of PGE-2 and various cytokines, especially II-1, II-6, and tumor necrosis factor.\textsuperscript{35,36} The level of inflammatory response is proportional to the volume of particulate UHMWPE produced. Since billions of wear particles are produced annually by a THA, the magnitude of the inflammatory response and resulting osteolysis can be great.

Osteolysis about well-fixed cemented and uncemented cups and stems has been reported.\textsuperscript{37-40} The majority of patients in whom massive osteolysis occurs are young, active patients with uncemented components.\textsuperscript{37,39}

Periprosthetic bone loss can result in aseptic loosening of a previously well-fixed prosthesis. Unfortunately, osteolysis is a clinically silent process, and massive bone loss frequently occurs prior to the clinical onset of pain and loosening. Once massive bone loss has occurred and the prostheses have loosened, revision of the components with structural allografts is required.

If osteolysis is discovered before massive bone loss has occurred and the components are still stable, then only an exchange of the modular liner and curvetting and bone grafting of the osteolytic lesion is required. This is a less morbid procedure than component revision and structural allografting. Thus, routine radiographic evaluation of asymptomatic patients is recommended at regular intervals.\textsuperscript{39}

Aseptic loosening of a previously well-fixed prosthesis also can occur as a result of linear wear of the cup or liner.\textsuperscript{4} When the femoral head wears a channel into the UHMWPE cup, angular movement of the prosthesis is restricted. This results in impingement of the prosthetic neck on the rim of the acetabular cup. Impingement causes shock loading of both the femoral stem and acetabular cup, which may lead to loosening of either or both components.

Late dislocations of previously stable THAs occasionally occur.\textsuperscript{41,42} In most instances, late dislocation is caused by wear of the UHMWPE cup or liner. The mechanism by which this occurs is similar to that which leads to aseptic loosening, namely, linear wear causes impingement. However, instead of loosening, the femoral neck levers on the rim and dislocates. Revision of the acetabular cup usually is required to prevent recurrent dislocation.

Because of the thickness of the UHMWPE, complete wear through and fracture of nonmetal-backed UHMWPE cups is rare.\textsuperscript{43,44} However, certain metal-backed cup designs implanted in the 1980s contained extremely thin liners when implanted in conjunction with 32-mm heads. As stated earlier, UHMWPE thickness as little as 1.8 mm can be found at the periphery of these cup designs. Vertical positioning of these cups can result in load bearing on this thin peripheral UHMWPE, and complete wear through and fracture of these liners is not uncommon.\textsuperscript{45}

Early reports of linear wear as great as 0.4 mm/year in Charley cups generated concern that many of these cups eventually would wear through and fail.\textsuperscript{8,9,46} Fortunately, longer term studies of these same cups have demonstrated the rate of linear wear decreases with time.

Charley and Halley\textsuperscript{2} measured the rate of linear wear in a cohort of patients at yearly intervals for 10 years and found the yearly wear rates for each patient decreased over time. For the entire cohort, the average wear rate decreased from 0.18 mm/year for the first 5 years to 0.10 mm/year over the last 5 years of the study, a decrease of 40%. In an in vitro report, using a hip joint simulator, Rose et al\textsuperscript{10} also found both linear and volumetric wear decreased over time.

These results are predicted by tribological laws. As surfaces wear against each other, they become more congruent. This increase in congruency occurs as a result of the wearing away of the surface asperities. Thus, adhesive and abrasive wear as well as creep decrease over time; only fatigue wear increases with time. Fortunately, in THA, adhesive wear, abrasive wear, and creep contribute more toward linear wear than does fatigue wear.

**SUMMARY**

As the longevity of THA improves, UHMWPE wear is becoming increasingly recognized as a clinical entity. Wear of the UHMWPE cup or liner usually is quantitated as linear wear, and most studies report linear wear rates of 0.10-0.20 mm/year.

Mechanisms of wear include abrasion, adhesion, and fatigue. Fortunately, abrasive and adhesive wear decrease over time as the bearing surfaces become more congruent. Factors affecting wear rates include component design, UHMWPE quality, and patient characteristics.

The use of ceramic femoral heads reduces the amount of in vitro UHMWPE wear. However, it is not known whether their in vivo performance will justify their increased cost.

Ultra high molecular weight polyethylene wear affects the clinical performance of THA through the mechanisms of osteolysis, aseptic loosening, dislocation, and component fracture. Hopefully, newer prosthetic designs and improved UHMWPE quality will decrease the future prevalence of clinically apparent UHMWPE wear.

**REFERENCES**


5. Livermore J, Ilstrup D, Morrey B. Effect
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1. Which type of wear plays a significant role in total hip arthroplasty (THA)?
   A. Abrasion wear.
   B. Adhesive wear.
   C. Fatigue wear.
   D. All of the above.

2. Free fragments of polymethylmethacrylate can lead to which type of wear?
   A. Two-body abrasive wear.
   B. Three-body abrasive wear.
   C. Fatigue wear.
   D. Adhesive wear.

3. Which type of wear becomes more prevalent with time?
   A. Two-body abrasive wear.
   B. Three-body abrasive wear.
   C. Fatigue wear.
   D. Adhesive wear.

4. Von Mises stresses are concentrated:
   A. At the bearing surface.
   B. 1-2 mm below the bearing surface.
   C. 5 mm below the bearing surface.
   D. None of the above.

5. Linear wear is greatest with which diameter femoral head?
   A. 22 mm.
   B. 26 mm.
   C. 28 mm.
   D. 32 mm.

6. Volumetric wear is greatest with which diameter femoral head?
   A. 22 mm.
   B. 26 mm.
   C. 28 mm.
   D. 32 mm.

7. All of the following are advantages of ceramic femoral heads over metallic femoral heads except:
   A. Increased wettability.
   B. Decreased coefficient of friction.
   C. Decreased rate of catastrophic failure.
   D. Decreased wear in in vivo tests.

8. In a classic study, Bartel et al demonstrated peak contact stresses experienced by a polyethylene component:
   A. Vary inversely with its thickness.
B. Is not affected by its thickness.
C. Increase with the thickness of the polyethylene.
D. None of the above.

9. Design characteristics of acetabular components that can lead to accelerated polyethylene wear include:
A. Deficiency of polyethylene thickness at the locking mechanism.
B. Incompetence of the locking mechanism resulting in motion between the polyethylene insert and metal backing of the cup.
C. Large-diameter femoral heads used with smaller diameter metal-backed cups.
D. All of the above.

10. Linear wear can result in all of the following except:
A. Late dislocation of THA.
B. Loosening of acetabular components.
C. Loosening of femoral components.
D. Infections of THAs.