New Insights into Wear and Biological Effects of Metal-on-Metal Bearings

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Background: Despite the renewed interest in metal-on-metal implants in the past two decades, the underlying wear mechanisms and biological effects are still not fully understood.

Methods: This paper first reviews the tribology of metal-on-metal bearings, bringing new insights into the interaction of wear and corrosion, and putting the characteristics and the potential origin of wear particles in perspective with the proposed wear mechanisms. It then summarizes the current knowledge on the biological effects of particles and metal ions in relation to these wear mechanisms.

Results: Tribochemical reactions play an important role in the wear of metal-on-metal joints. The generated tribomaterial, which progressively forms by mechanical mixing of the uppermost nanocrystalline zone of the metal surface with proteins from the synovial fluid, governs the wear rate and influences the corrosive behavior of the bearing. Nanometer-sized wear particles may initially originate from the passivation layer covering the implant surface and then detach from this tribolayer. The inflammatory response observed surrounding metal-on-metal implants appears to be lower than that around metal-on-polyethylene implants. However, metallic byproducts, which can complex with proteins, may lead to a T lymphocyte-mediated hypersensitivity response.

Conclusions: The tribolayer appears to have beneficial effects on the wear rate. Much information has been gained on wear particle characteristics, but the exact mechanisms of particle detachment remain to be further elucidated. Excessive wear along with a hypersensitivity response may be at the origin of the early adverse tissue reactions that have been recently reported in some patients with metal-on-metal implants.

Clinical Relevance: Future development of new methods to improve the tribolayer retention and optimize the tribo-corrosive properties of the implant may minimize the clinical impact of implant wear and immune responses.

Since the introduction of the first generation of metal-on-metal bearings in the early 1960s, progress has been made in understanding and controlling manufacturing variables. There has been a renewed interest in metal-on-metal implants in the past two decades because of the high wear performance compared with conventional metal-on-polyethylene bearings. Also, large femoral heads can be used with metal-on-metal implants, allowing hip resurfacing designs that preserve the proximal femoral bone stock. Progress has been largely based on empirical information, and the underlying wear mechanisms are not well understood. The release of metal ions, which can complex with proteins¹⁻³, and the formation of

nanometer-sized wear particles⁴⁻⁶ have raised concerns regarding metal hypersensitivity and potential genotoxicity.

Histological studies of the tissues surrounding second-generation metal-on-metal hip replacements generally support the primary rationale for the reintroduction of metal-on-metal bearings. Indeed, the extent of the inflammatory reaction and the presence of foreign-body giant cells appear to be much less marked than in tissues from conventional metal-on-polyethylene components⁷. However, a major cause for concern with metal-on-metal hip replacements has recently emerged because of increasing reports of unexpected early adverse local tissue reactions⁸⁻¹³, which compromise the functionality and survivorship

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of these implants. In some cases, even severe systemic complications have been associated with metal-on-metal implants¹⁴. These adverse reactions are of concern because metal-on-metal bearings currently constitute approximately 35% of the >300,000 primary hip replacements performed annually in the U.S.¹⁵.

In the present study, the current knowledge about metal-on-metal wear mechanisms, including new findings regarding the interaction of wear and corrosion, is reviewed first. Wear particle characteristics and their potential origin are then discussed. Finally, these new findings are placed in context with observed biological reactions.

Wear, Tribochemical Reactions, and Metal-on-Metal Tribolayers

Wear is defined as loss of material from a tribological system as a result of energy dissipation. Typically, the energy is introduced by friction. Wear is not a material property (like strength, ductility, or hardness) but depends on the structure of the tribological system. This means that counterbody, interfacial material (e.g., lubricant and intrinsic or extrinsic particles) and the environment (e.g., the temperature or pH of the surrounding media) are similarly important in the generation of wear. In fact, the specific conditions often define the acting wear mechanism, which itself defines how many particles per stroke and/or time increment are generated. Currently, there are four major known wear mechanisms, which are either purely mechanically dominated (abrasion and surface fatigue) or chemically and/or mechanically mixed (adhesion and tribochemical reactions). All of them can be subdivided into several submechanisms, depending on the nature of the specific contact situation and their interaction. Details have been summarized elsewhere¹⁶.

Studies have suggested that the governing wear mechanisms at the metal-on-metal interface are not adhesion and/or abrasion as in conventional hip bearing types, but predominantly tribochemical reactions and surface fatigue^{17,18}. These

tribochemical reactions result in the reaction of the metal surface with the synovial fluid and form a tribomaterial at the surface, also referred to as a *tribolayer* because it is generated at the surface. The term *tribomaterial* was introduced by Rigney et al.¹⁹ to point to the fact that this material is quite different from the base material. In the case of metal-on-metal joints, the tribomaterial shows a nanocrystalline structure with a grain size between 30 and 70 nm (note the size similarity to wear particles as shown in Figure 1, C and reviewed later) and consists of a mixture of organic, ceramic, and metallic constituents^{17,18}.

Cobalt-chromium-molybdenum (CoCrMo) alloy recrystallizes under the surface because of the influence of shear from a face-centered cubic to a hexagonally closed, packed crystal lattice, which results in the nanometer-sized grains²⁰⁻²². The small grains can rotate to accommodate the frictional shear stresses introduced by the counterbody, and thus dissipate energy without particle detachment. This is one of the reasons why CoCrMo can articulate in the ultramild sliding wear regime with a material loss of <1 nm/hr. Also, the rotation of grains results in the incorporation of the pseudosynovia, a process that has been termed mechanical mixing²³. It can be attributed as a submechanism to tribochemical reactions because the chemical composition and properties of the uppermost material have been changed. In the case of metal-on-metal joints, an organometallic composite is generated on the basis of the remains of the lubricant (presumably denatured proteins) and metallic nanoparticles of the upper surface layer²². The thickness of the entire nanocrystalline zone ranges from 100 to 400 nm, while the tribomaterial itself is the near-surface fraction of it with a thickness between 0 and 300 nm^{22,24}.

It is important to understand that a metal-on-metal bearing can only stabilize in the ultramild wear regime in the presence of adhering tribomaterial. While such tribomaterial has been observed on the surface of current metal-on-metal implants^{24,25} and is shown on a large-diameter ASR cup (articular

Fig. 1
A: Scanning electron micrograph of a tribolayer on a large-diameter cup. B: Transmission electron micrograph of a cross-sectional cut through a tribolayer. Note the carbon layer and the embedded nanocrystals. C: Transmission electron micrograph of wear particles generated by hip simulator testing of a metal-on-metal implant (cast alloy) in 95% bovine serum for 0 to 0.25 million cycles, showing an example of a particle containing Cr and O (1), an example of a particle containing Co and Cr with Cr>Co (2), and an example of a particle containing Cr and Co with Co>Cr (3). (Figure 1, C reprinted, with permission, from: Catelas I, Medley JB, Campbell PA, Huk OL, Bobyn JD. Comparison of in vitro with in vivo characteristics of wear particles from metal-metal hip implants. J Biomed Mater Res B Appl Biomater. 2004;70:167-78.)

surface replacement; DePuy, Warsaw, Indiana) and a 28-mm Ultima head (DePuy) in Figure 1, A and B, respectively, these tribolayers seem to be absent and/or worn off under high-stress conditions. For example, Pourzal et al.²⁴ demonstrated that the tribolayer is absent in the stripe wear region of metal-on-metal joints (the stripe wear region is the area that interacts with the acetabular rim because of microseparation)²⁶. It is also speculated that the implantation of the acetabular component in excessive anteversion and/or abduction may destabilize the layer and lead to excessive wear. This agrees with clinical observation²⁷ and experimental hip wear testing²⁸. Hence, a better understanding of the kinetics of the tribomaterial formation and removal at the hip joint could be crucial for improved clinical outcome. In particular, it is necessary to define the mechanical boundary conditions for optimal bearing performance. This may lead to alloy formulations and implant designs that exhibit a more robust tribomaterial and are less susceptible to wear.

Tribocorrosion Behavior of the Nanocrystalline and Mechanically Mixed Zone

While the tribomaterial should have advantageous effects on metal-on-metal wear, the corrosive and tribocorrosive behavior has yet to be evaluated. In order to report a positive effect, the corrosion behavior of an implant with a tribolayer must be superior compared with a (worn) CoCrMo surface without a tribolayer. Such questions are best addressed with use of an electrochemical approach with a standard three-electrode corrosion cell and an attached potentiostat²⁹.

Muñoz and Mischler³⁰ investigated the interaction of albumin and phosphates present in the body fluids on the passivation behavior of CoCrMo alloys. The study revealed that phosphates and proteins played an important role in the electrochemical properties of the metal-oxide-electrolyte interface. Mathew et al.³¹ reported that physiological conditions (simulated with bovine calf serum), and in particular the presence of proteins, improved the passivation kinetics of the CoCrMo alloy. However, at the same time, the pitting potential decreased, suggesting that pitting corrosion is more likely in a protein-containing solution. The presence of pits has been reported on the articulation of retrieved hip implants³², and thus pitting corrosion is of concern as a potential source of metal ions.

These studies do not take into account the tribolayer that forms during articulation. When using samples with artificially prepared surfaces (nanocrystalline without proteins and nanocrystalline with tribomaterial), Mathew et al. recently reported a higher anodic potential of the metal-on-metal heads with tribomaterial, suggesting a more noble behavior with better corrosion resistance than heads without tribomaterial coverage³³. The variation in potential is, however, only an indicator of corrosion tendency, and further investigations are necessary to fully understand the interaction of the tribomaterial on the corrosive behavior in metal-on-metal joints. In particular, it is unclear how the corrosive properties of the tribomaterial change in the presence of contact movement, as is the case during articulation of the hip joint implants.

To better understand the synergism between wear and corrosion³⁴, the following study was conducted: a 28-mm-diameter alumina ball was articulated against cylindrical pins of high-carbon CoCrMo (0.24% carbon, 12-mm diameter; ATI Allvac, Monroe, North Carolina) in a specifically designed test rig incorporated in an electrochemical cell. The flat surfaces of the pins were polished to a roughness R_a better than 10 nm with a nanocrystalline microstructure at the surface. Under potentiostatic conditions at a fixed potential close to the free potential, the wear tests were performed with use of a normal load of 16 N with ball rotation of $\pm 15^\circ$ at 1 Hz for 100,000 cycles. Diluted bovine calf serum (30 g/L protein) was used as the lubricant and electrolyte. Electrochemical impedance spectroscopy measurements were taken before and after the test. The total material loss was determined by three-dimensional profilometry, and the loss due to corrosion was calculated with Faraday's law. It was found that the wear scars on the pins showed the formation of a tribolayer. The weight loss due to wear (K_w) accounted for the majority of the total loss (K_{wc}), but the loss due to corrosion (K_c) was non-negligible, as shown in Figure 2 (where $K_{wc} = K_w + K_c$). The synergy ratio K_c/K_w of 0.26 indicates that corrosion plays an important role in the overall degradation process³⁵, which is, a priori, not expected from corrosion experiments without mechanical activation of the surface. Therefore, decreasing or eliminating the synergistic corrosion component would lead to considerable reductions in the material loss of metal-on-metal bearings. Methods to accomplish such reductions could entail alloy formulations and/or surface textures that exhibit a more robust tribolayer. For example, a microtopological surface could anchor the tribolayer

Fig. 2

Total weight loss (K_{wc}) of high-carbon wrought CoCrMo in bovine calf serum after tribocorrosive attack (100,000 cycles) at a fixed potential close to the free corrosion potential (E_{corr}). The total weight loss is a combined effect of corrosion and wear, and its respective parts K_c and K_w are shown accordingly. Note that the weight loss due to corrosion (K_c) is much higher than the weight loss during pure corrosion at similar E_{corr} conditions.

and thus help to better withstand shear forces. At the same time, the valleys could serve to capture particles during the initial wear cycles (referred to as the run-in period) of the bearing.

Wear Particle Characteristics

Multiple studies have described metal-on-metal particle characteristics, but they remain difficult to compare because of differences in the metallurgy of the prosthetic component alloys and differences in the isolation and characterization protocols that can affect the particles as demonstrated by Catelas et al.^{36,37}. Despite that, there is now a general consensus that the average particle size ranges from about 30 to 100 nm⁴⁻⁶. Particle shape and composition, however, vary more from study to study. To understand the potential effects of the alloy and the number of loading cycles in a hip simulator (i.e., in vitro), as well as implant design and implantation time in vivo, Catelas et al. conducted several studies^{5,38,39}. The same particle isolation and characterization protocol (developed by those authors and recently incorporated in International Organization for Standardization [ISO] 17853)⁴⁰ was used for the serum in a hip simulator and for the tissue samples to avoid confounding factors inherent to the use of different protocols.

In a first study comparing the effects of alloys and the number of loading cycles in a hip simulator, results showed that, for all three CoCrMo alloys tested (high-carbon wrought, low-carbon wrought, and cast), the majority of the particles were round to oval and averaged about 52 nm in length with only small differences due to the alloy⁵. Energy-dispersive x-ray analysis revealed that these particles (which appeared lightly contrasted under transmission electron microscopy) contained Cr and O, but no Co, and were therefore likely chromium oxide particles, as they appeared lightly contrasted under transmission electron microscopy. However, some CoCrMo particles (darker under transmission electron microscopy) were also found, depicting varying ratios of Co and Cr, and were either small round or larger elongated particles. (Figure 1, C illustrates particles generated with the cast alloy.) The small round CoCrMo also usually depicted a peak of carbon. The proportion of these CoCrMo particles appeared to be associated with the number of loading cycles in the hip simulator, with more CoCrMo particles during the run-in than the steady-state wear period. Finally, more CoCrMo particles were found with the low-carbon wrought alloy than with the high-carbon wrought and cast alloys, although the majority of the particles remained chromium oxides.

When the effect of implant design and implantation time were analyzed, the results showed that, with the exception of hip replacements implanted for less than fifteen months that depicted almost exclusively chromium oxide particles, all other implants showed the presence of some CoCrMo particles, mainly needle-shaped. The percentage of these needle-shaped particles was the highest with hip replacements implanted for more than twenty years³⁸. The average particle lengths (49 to 57 nm) were not markedly different between the different designs and implantation times except for the current design implants retrieved within fifteen months, which had a significantly

smaller average length of 39 nm. No significant differences in particle characteristics were detected between hip resurfacing and stem-type devices. Overall, that study showed that implantation time appeared to affect particle characteristics (mainly the amount of CoCrMo particles), but implant design did not have a significant influence. Many manufacturers treat the surfaces before packaging (e.g., with nitric acid to increase the thickness of the protecting chromium-oxide layer). Hence, differences observed in particle characteristics between the very short (less than fifteen months) and longer-term implants might have been related to such chemical treatments. Once the passivation layer is worn away, CoCrMo particles are generated as well. It should, however, also be noted that the very short-term implants were revised for early clinical complications (e.g., dislocation or heterotopic ossification). The wear mechanisms and the wear rates might thus have been different and possibly contributed to the differences observed in the particle characteristics, especially considering that the volumetric wear of retrievals reported in the literature has suggested that the initial wear rates should be high^{41,42}. As such, it can be concluded that any differences between original and more current metal-on-metal implant designs would probably be determined by the overall implant survival time rather than by differences in particle characteristics themselves³⁸.

Finally, a study compared particles generated in the orbital bearing simulator (up to two million cycles) or isolated from tissues retrieved after one to forty-three months³⁹. The results showed that the particles isolated from two patients at twenty-three and forty-three months had an average length, shape, and composition that were most comparable with those of the particles generated in the hip simulator during the run-in wear period (particles analyzed were generated between 0 and 0.25 million cycles). In this study, implants made of the same cast alloy to the same specifications and by the same manufacturer (Wright Medical Technology, Arlington, Tennessee) were selected to avoid confounding factors inherent to the metallurgy of the component alloys. Overall, this study supported the results of a large clinical retrieval study, suggesting that a run-in wear regime might occur in vivo for some six to thirty-six months⁴¹.

Wear Particle Origin

Some of the previous studies that have identified chromium oxide particles in vivo had hypothesized that Co may have been dissolved in the tissue environment, leaving Cr and O⁴. Other studies that have described particles with varying proportions of cobalt, ranging from approximately that of the original alloy material (about 57%) to zero, had interpreted this reduction as an indication of in vivo corrosion⁴³. Another possibility that has been reported is that chromium oxide particles may be produced by wear of the passivation layer covering the implant surface, or may originate from some oxidized chromium carbides⁵. However, after run-in of the implant, the oxide film likely exhibits a thickness of 2 nm to a maximum of 10 nm only⁴⁴, which would be too thin to be the origin of the wear-generated chromium oxide particles⁴⁵. It is,

however, possible during the run-in period of the implant. Catelas et al. further suggested that small CoCrMo particles (depicting a peak of carbon and a higher peak of Cr than Co) may originate from carbides, and larger ones (depicting a higher peak of Co than Cr) may come from the bulk material. Energy-dispersive x-ray analysis peaks were considered to be likely proportional to the Co and Cr elements, considering the very similar atomic number of Co and Cr elements⁵. However, further analytic work was still required to determine with more certainty the origin of these particles.

In a recent study, Pourzal et al. used energy-filtered transmission electron microscopy and diffraction pattern analysis to gain further knowledge on the chemical composition and the crystalline structure of the particles⁴⁵. Results showed that the smallest chromium oxide particles generated from a high-carbon wrought alloy cycled in an EndoLab hip simulator had the lattice structure of Cr₂O₃ and depicted lattice defects, suggesting that these particles had been likely subjected to high mechanical and chemical reactions. These small (5 to 15-nm) Cr₂O₃ particles appeared to be flaking off larger particles that were depicting a very high intensity of oxygen, as well as chromium, and only background of Co. Other larger particles depicted Co locally. It is possible that these particles may have been generated from the tribomaterial as described earlier in the present paper and in the literature^{17,20-22}. Previous studies have noted that in tribosystems operating in the ultra-low wear regime, particles are generated from tribolayers formed *in situ* rather than in the underlying deformed subsurface zones^{46,47}. Nevertheless, the exact mechanism of particle detachment and the absence of Co in most of the particles are still not fully understood, since particles should exhibit Co if they are originating from the nanocrystalline zone. It is possible that particles become oxidized by mechanical mixing within the

tribolayer or in the contact area between the femoral head and the cup after their detachment⁴⁵. Through oxidation, these metallic particles could be a source of metal ions.

Biological Effects

Most of the cell culture studies on the biological effects of metal-on-metal particles have been conducted with use of CoCrMo particles, mainly in the micrometer range⁴⁸⁻⁵¹. Few studies have used CoCrMo particles in the nanometer range^{52,53}, but the biological effects of chromium oxide particles have not been described specifically. This is likely related to the lack of knowledge about the precise characteristics of the metal-on-metal particles until recently, as well as the difficulty of generating chromium oxide particles in the nanometer range for cell culture studies. In a recent study analyzing the macrophage response to commercial nanometer-sized Cr₂O₃ particles, VanOs et al. demonstrated that 60-nm-sized Cr₂O₃ particles, when present in very large concentrations (up to 3.5 million particles per cell), could induce a significant decrease in the total cell number (Fig. 3) and a significant increase in cell necrosis⁵⁴. However, tumor necrosis factor- α release remained at low levels, similar to those in control samples (i.e., cells with no particles). This study suggested that overall, nanometer-sized Cr₂O₃ particles, a stable form of chromium oxide ceramic, induced a lower inflammatory response compared with previously reported micrometer-sized ultra-high molecular weight polyethylene particles at lower concentrations⁵⁵.

In vivo studies have noted the presence of cytokines associated with osteolysis in tissues surrounding metal-on-metal implants, demonstrating the presence of a nonspecific inflammatory response as previously described with metal-on-polyethylene implants, but the extent of such response and the presence of foreign body-type giant cells appeared to be less

Fig. 3

Effect of 60-nm Cr₂O₃ particle number (per cell) on total J774 mouse macrophage number after twenty-four-hour incubation. A half-million macrophages were initially incubated for each condition, in tubes containing 1 mL of culture medium. Tubes were put in rotation to allow constant resuspension of cells and particles. After twenty-four-hour incubation, total cell numbers (viable and dead) were measured with use of a hemocytometer. Results are given as the mean and standard deviation of three experiments performed in triplicates.

substantial in tissues surrounding metal-on-metal implants^{7,56,57}. In addition to this nonspecific inflammatory response, the presence of lymphocytic infiltrations around metal-on-metal implants has generated a cause for concern^{56,58-61}, suggesting a potential hypersensitivity response to metal wear products. The mechanisms and causes of this hypersensitivity remain largely unknown. They may be due to metal degradation products that can complex with serum proteins¹⁻³ to form haptens⁶², to which individuals may have a different response threshold⁶³. It is also possible that proteins complexed with the particles detaching from the tribolayers, as described earlier, form haptens, especially considering that these proteins are likely denatured from exposure to high shear rates and elevated temperatures. Implant-related hypersensitivity response has been thought to be a delayed type-IV reaction⁶². However, in a study on failed modern metal-on-metal total hip replacements, Willert et al. reported the presence of plasma cells, B lymphocytes, and massive fibrin exudation that is not characteristic of a delayed type-IV hypersensitivity reaction⁶¹. The authors described this reaction histologically as an aseptic lymphocyte-dominated vasculitis-associated lesion (ALVAL) or as a lymphocyte-dominated immunological answer (LYDIA).

More recently, some studies have described early adverse tissue reactions, including pseudotumors (described as soft-tissue masses or fluid-filled bursae)^{8,9} that can lead to devastating short-term implant failures. Some studies noted revision rates of up to 3.2% for hip resurfacing arthroplasty at thirty-five months and 6% for femoral stem-type devices at forty-one months¹⁰. These alarming reactions have led to growing concerns within the orthopaedic community during the last year. The causes of these reactions, however, are not well understood. Some studies have described an association between these reactions and greater wear of the retrieved components^{10,12}. The importance of implant size and implant design (clearance and cover [arc angle]) has been noted. Also, acetabular component positioning and femoral head-neck offset influence the risk of impingement and edge-loading that are usually associated with high wear rates. On the other hand, Campbell et al. reported that, of thirty-two hip replacements revised because of pseudotumor, some patients had a high ALVAL score in the absence of high wear, suggesting a hypersensitivity origin¹³. Hence, the origin of these early adverse reactions is likely multifactorial and may be due to excessive wear, but also possibly due to metal hypersensitivity, a combination of the two, or even a yet unknown cause¹³. Pseudotumor-like reactions have also been reported in non-metal-on-metal bearings⁶⁴⁻⁶⁶. In these cases, the histological findings showed accumulations of macrophages and giant cells, suggesting an excessive wear origin.

Finally, metal soluble and particulate products have generated concerns about potential genotoxicity, especially considering their propensity to disseminate systemically, as depicted by elevated levels of metal ions in serum, urine, whole blood, and erythrocytes of patients with metal-on-metal implants⁶⁷⁻⁷⁰, and particles observed in the liver and the spleen⁷¹. Multiple studies have shown the potential toxicity of Co and Cr ions, with Co²⁺ being more toxic than Cr³⁺ in several investigations⁷²⁻⁷⁵ and Cr⁶⁺

being rapidly soluble and able to induce both mutagenic and replication-blocking DNA lesions in cultured cells⁷⁶. Milosev and Remskar identified small amounts of Cr⁶⁺ in the surface layer of retrieved implants⁷⁷. In addition, some studies have described an increase of aneuploidy, chromosome translocation, and DNA damage in cultured cells exposed to CoCrMo particles in vitro, or a higher chromosomal aberration rate in cells adjacent to the prosthesis at revision surgery^{78,79}. Overall, those studies showed potential genotoxicity of metal ions and wear particles. However, the clinical consequences of the potential DNA and chromosome damages, if any, remain unknown, and future epidemiologic studies should include comparison between patients with implants of different composition and at long postoperative survivals⁶³.

Conclusion

Tribochemical reactions play an important role in the wear of metal-on-metal joints. The generated tribomaterial, which progressively forms by mechanical mixing of the upmost, nanocrystalline zone of the metal surface with proteins from the synovial fluid, governs the wear rate and influences the corrosive behavior of the bearing. Initial studies have suggested that such a tribolayer has beneficial effects on the wear rate; however, a stronger retention may be warranted to better withstand high-stress situations. The influence of the tribolayer on the corrosion behavior needs to be further evaluated. Much information has been gained on wear particles, which may initially originate from the passivation layer covering the implant surface, and then detach from the tribolayer. However, the exact mechanism of particle detachment and the absence of Co in most of the particles remain to be further elucidated.

The inflammatory response observed surrounding metal-on-metal implants appears to be lower than that around conventional metal-on-polyethylene implants. However, in addition to this nonspecific inflammatory response, metallic by-products complexed with serum or synovial fluid proteins or denatured proteins possibly originating from the tribolayer covering the implant may lead to a T lymphocyte-mediated immune response. Such response along with excessive wear, combined or separately, may be at the origin of the early adverse tissue reactions that have been recently reported in some patients with metal-on-metal implants. Unfortunately, as of now, there is no generally accepted screening method to assess the patient's risk of developing such reactions. However, future development of new methods to improve the tribolayer retention and minimize pitting corrosion may minimize the clinical impact of implant wear and immune responses. ■

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