TRIBOCORROSION: CONCEPTS AND CLINICAL RAMIFICATIONS

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It is truly an honor to be delivering the 2014 John Charnley Lecture. I consider Sir John the father of modern hip replacement surgery and a true visionary in the field of orthopedic surgery. In Charnley’s authoritative and prophetic 1978 textbook “Low Friction Arthroplasty of The Hip: Theory and Practice” there is no mention of the word tribocorrosion, the theme of this 2014 Charnley Lecture. However, I do believe that he does anticipate this relatively new concept in the field of orthopedic implantology by the following quote. “…… it is still possible that the last word has not yet been said on the ultimate nature of lubrication in animal joints and as is commonly the case in matters of lubrication, a mixed regime of fluid, film and bodily lubrication probably exists, with Nature having discovered a unique means of making a mixed regime”. I believe this quotation anticipates some of the more recent findings on the nature of lubrication in hard-on-hard bearings as well as the complexity of the physical, chemical and biological processes occurring in association with a total hip replacement.

Tribocorrosion can be defined as an “irreversible transformation of material in tribological contact caused by simultaneous physicochemical and mechanical surface interactions.” Tribocorrosion is an integrative approach to study implant performance employing the disciplines of corrosion science and engineering (the physicochemical component) and tribology (the physicomechanical component). By combining the theories, techniques and conventions of the two disciplines a more complete understanding of the in vivo performance of total hip replacement components will emerge, providing more robust and predictive models of the in situ degradation of metal implants.

Corrosion is an electrochemical process involving a series of oxidation and reduction reactions that are governed by thermodynamic properties as exemplified by the Nernst equation. However,
thermodynamic calculations alone do not account for the in vivo corrosion behavior of metallic implants; the spontaneous formation of an oxide film (chromium oxide in the case of cobalt-chromium alloys) on the metal surface results in a phenomenon called passivation whereby the rate of redox reactions are dramatically reduced by kinetic considerations. That is, the thin (tens of nanometers) passive film limits the diffusion of oxidizing species from the surrounding fluids and metal ions and electrons from the implant surface. In contrast, the field of tribology primarily concerns itself with the mechanics of surface interactions and the discipline is generally approached using concepts from fluid mechanics, solid mechanics and materials science to characterize the underlying wear mechanisms. The discipline of tribocorrosion combines concepts from electrochemistry, solid and fluid mechanics and materials science and employs experimental methodologies that are a combination of those used in conventional corrosion testing and conventional wear testing.

Corrosion and tribological processes are synergistic with regard to the release of particulate and ionic degradation products: Passive films are removed by wear causing metal ion release and the reformation of a passive film which is then removed again by wear, and so forth. It has been recently estimated that this synergistic component can account for 58% of the volume loss from a metal bearing surface in comparison to summation of volume loss from corrosion alone and wear alone.3 In a situation where accelerated corrosion can occur, for example in a relatively low pH environment, this synergistic component can be even greater.3 Tribocorrosion occurs not only at metal-on-metal bearing surfaces, but also at metal/metal modular junctions where there is a potential for micromotion between the two components. It is now believed that many of the metal-on-metal clinical failures that had been attributed to debris produced by accelerated wear at the bearing surface may in fact be due to debris generated from tribocorrosion at the modular head-neck junction.4
There are a number of prevention strategies that can be deployed to minimize tribocorrosion. For example, at the modular junctions relative micromotion can be minimized by having tight tolerances, optimal neck length and head size to minimize torsional loads, and optimal geometry and surface finish. Regarding geometric parameters, flexural rigidity of the neck has emerged as one factor that can predict the propensity for tribocorrosion at modular junctions. Additionally, appropriate intra-operative assembly of modular junctions is required to minimize micromotion. In the case of metal-on-metal bearing surfaces, tribocorrosion may be minimized by optimizing the lubrication regime and by improving the tribocorrosion resistance of the base alloys, meaning that the reformed passive films after wear display properties which can better cope with the specific contact situation. In a study of retrieved metal-on-metal bearing surfaces, a tribochemical reaction layer was identified that was, in part, composed of graphitic carbon. Graphitic carbon can serve as an effective solid state lubricant and a barrier to tribocorrosion. However, if this layer does not stabilize the tribocorrosion resistance can be compromised. Therefore, one promising strategy to improve the performance of metal on metal bearing surfaces is to develop methods to stabilize the solid-state lubricant on the surface.

Tribocorrosion has emerged as a clinically relevant issue in contemporary total hip replacements. This is true not only for metal-on-metal bearings, but for metal-on-polyethylene bearings in which the femoral component has modular metal/metal junctions. In our center we have been studying patients who presented with adverse local tissue reactions (ALTRs) associated with moderate to severe tribocorrosion at the head/neck junction. The implants involved included six different designs from four different manufacturers. We found that, in general, this is a diagnosis of exclusion. The patients typically present with hip pain, but many will present with the new onset of recurrent dislocations. Thus, in patients with metal-on-polyethylene bearings with modular heads
who present with unexplained pain, particularly those that experience late recurrent dislocations, the index of suspicion should be high that an ALTR secondary to tribocorrosion of the head/neck junction is present.

The keys to establishing this diagnosis prior to revision surgery are elevated serum metal levels, in which the serum cobalt is elevated out of proportion to serum chromium, the presence of periarticular fluid collections and/or masses on metal artifact reduction sequence magnetic resonance imaging (MARS-MRI). Interestingly, the majority of patients with this entity have femoral head sizes of 32 millimeters or less --- this is not strictly a “big head” problem. In addition, a preponderance of these cases is associated with cementless cobalt-chromium femoral components. At mean two year follow up, modular component exchange with a ceramic head and a titanium sleeve has proven to be an effective treatment for ALTRs associated with tribocorrosion at the head/neck junction, but longer term follow-up is required to determine whether these short term positive results are maintained.

ALTRs have also been reported in association with tribocorrosion at the neck/body junction in modular neck femoral components. We have reported on this phenomenon in an implant system that was subsequently recalled from the market due to this problem. As is the case for ALTRs associated with head/neck tribocorrosion, ALTRs associated with neck/body tribocorrosion can be diagnosed by elevated serum cobalt levels out of proportion to elevations in serum chromium and by MARS-MRI findings of peri-articular fluid and/or masses. The treatment in this situation is femoral component revision.

The relatively recent realization that tribocorrosion at modular junctions can lead to ALTRs has stimulated a reexamination of our understanding of the pathogenesis of ALTRs in association with
metal-on-metal total hip replacements. In light of recent reports that the amount of material loss from modular junction tribocorrosion can exceed that from the bearing surface in metal-on-metal total hip replacements in certain cases, it is plausible to conclude that the modular junction(s), not the bearing surface, were the ultimate cause of failure due to ALTR in those cases. Thus, simple bearing surface exchange in the treatment of ALTR in association with a metal-on-metal total hip replacement with head/neck or neck/body modularity may not address the primary wear generator; modular junctions should also be carefully assessed for tribocorrosion damage and treated accordingly, as described above.

Tribocorrosion of modern metal implants can lead to real clinical problems. It is incumbent on orthopaedic surgeons, engineers, materials scientists, implant pathologists, molecular biologists, cell biologists and implant manufacturers to elaborate the mechanistic basis of tribocorrosion of metal implants and its attendant biological consequences in order to develop strategies to prevent this phenomenon. It is likely that ALTRs associated with tribocorrosion occur as the result of a complex multifactorial process involving implant, surgeon and patient factors. In the spirit of Sir John Charnley, a comprehensive and systematic scientific approach to this problem will likely lead to solutions and improved patient outcomes. A key to the solution may lie in exploiting what Sir John described as “......Nature finding a unique means of making a mixed regime.”

Thank you for the privilege of being the 2014 Charnley Lecturer.
REFERENCES


