AAOS Now

The Challenge of Corrosion in Orthopaedic Implants

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Corrosion has been a persistent challenge in orthopaedics. Even Sir John Charnley noted the critical challenges of corrosion in the design of trauma and arthroplasty implants. The idea that different metals cannot be used in the same implant secondary to galvanic corrosion is a basic scientific concept in orthopaedic residency education.

But in actual practice, multiple different metals are combined to improve overall implant design. In hip arthroplasty, for example, cobalt-chrome heads fitted to titanium stems are the industry standard. Where is the disconnect between standard practice and textbooks?

Galvanic corrosion

Galvanic corrosion is the electrochemical potential difference between two dissimilar metals. In theory, one metal becomes the anode and the other the cathode. The active metal, the anode, is under attack from the more resistant metal, resulting in the corrosion. Given this basic knowledge that a circuit established between two different metals leads to aggressive corrosion, common sense would dictate not using multiple metals in an orthopaedic implant.

The passivation layer is the essential component that enables implants composed of multiple alloys to avoid galvanic corrosion. Metals are not inert. Oxide layers that develop in vivo or as a consequence of surface treatments protect implants from corrosion. In essence, the metal oxide film becomes an insulator, protecting the metal from direct exposure with the electrochemical milieu.

Not all metals can form a stable passivation film. Classic stable “passive” metals include titanium, chromium, and molybdenum alloys.

Corrosion in orthopaedic implants is really about the breakdown of this passivation film. Chemistry and mechanical wear erode the dynamic oxide film that insulates the implant and are key to both wear and corrosion. In essence, wear and corrosion become intertwined, each dependent on the other, and accelerate component breakdown.

Passivation layers

Passivation layer dynamics is the key concept behind three types of corrosion: pitting, crevice, and fretting. In pitting, localized dissolution of the metal oxide film and formation of cavities occur at rates faster than the build-up of the metal oxide layer. Crevice corrosion is based on a similar mechanism, but occurs in stagnant areas where fluid diffusion is limited.

In crevice corrosion, an increase in the concentration of chloride ions, low pH, and low oxygen tension accelerates breakdown of the passivation layer by creating conditions that increase the solubility of the metal oxide film. Fretting is mechanically assisted crevice corrosion, in which mechanical destruction of the passive film allows crevice corrosion to predominate. The combination with the highest potential for corrosion is stainless steel and cobalt-chrome; this combination has the weakest passivation layer, resulting in a lower threshold for corrosion.

Galvanic corrosion can potentially be avoided when a stable passive film develops on metal components and motion and local chemistry that can cause crevice and fretting wear are eliminated. When these criteria—a stable passive layer and elimination of motion between metals—are met, different metal alloys can be used in the same implant.

Hip arthroplasty implants

A classic example of mixing metals can be seen in total hip arthroplasty (THA) designs. Mixing metals first became advantageous after the introduction of porous-coated cementless arthroplasty components, such as the Harris-Galante, porous coated anatomic (PCA), and anatomic medullary locking (AML®) designs, which required metal alloys that provided a good bearing surface and were optimized for bone ingrowth.

Initially, the components in these models were either entirely cobalt-chrome or a mix of titanium alloy and cobalt-chrome. After early studies reported initial outcomes of hip pain and expressed concern about the high stiffness of cobalt-chrome femoral stems, the standard shifted to a cobalt-chrome head and a titanium alloy femoral stem.

What motivated the need for multiple material composition of the THA femoral component? Cobalt-chrome is an excellent material for the design of a femoral head. Its hardness is ideal for decreasing wear as a bearing surface. It is not as ideal for a femoral stem, given its significantly higher modulus of elasticity compared to bone.

Titanium alloys, on the other hand, are better as femoral stem components because they allow more bone ingrowth and have a closer modulus of elasticity to bone, resulting in less stress shielding of the implant. Titanium is also more biocompatible, fatigue-resistant, and easier (from a manufacturing perspective) to shape with the necessary geometry and substrate to encourage bone ingrowth.

The crucial connection for these two components occurs at the modular taper interface between the femoral head and neck. The taper essentially locks the head onto the neck. Friction prevents movement, but the junction is not impervious to fluid. These modular junctions can become the weak point in arthroplasty design, susceptible to wear and breakdown.

Multiple studies have demonstrated that crevice and fretting corrosion (ie, mechanically assisted crevice corrosion)—not galvanic corrosion—are the dominant modes of corrosion of the passivation layer at the head-neck taper interface. Even without galvanic corrosion, however, the corrosion can still be significant.

Mechanically assisted crevice corrosion can lead to numerous problems, including implant failure from loss of mechanical integrity, third-body wear due to trapped particles between the articulating surfaces, osteolysis, and localized granulomatous reactions. Recent reports of pseudotumor formation in well-fixed metal-on-polyethylene hip implants are likely the result of mechanically assisted crevice corrosion.

Fretting corrosion can be increased in a large metal-on-metal head due to the greater surface area of the bearing and the increased forces across the taper junction. When modularity is introduced at the neck, adding another taper junction, the debris from fretting corrosion can increase significantly (Fig. 1).

Fig. 1 *Modularity can be the weak point in the implant design and the source of more debris from corrosion.*
Courtesy of Kenneth L. Urish

Corrosion continues to be a problem in orthopaedic implant despite more than four decades of experience. The passivation layer prevented initial fears of galvanic corrosion between certain pairs of mixed metals from occurring, but fretting corrosion is a major contributor to debris in many newer designs. When the correct criteria are met, crevice corrosion and fretting can lead to early implant failure. All surgeons should be cautious when adding levels of modularity that can add more debris to an implant system.

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Disclosure information: Dr. Urish—no conflicts. Dr. Anderson—Pioneer Surgical; Stryker; Aesculap; Expanding Orthopedics; SI Bone; Spartec; Titan Surgical; Clinical Orthopaedics and Related Research; Journal of Bone and Joint Surgery–American; Journal of Orthopaedics and Traumatology; Journal of Spinal Disorders; Neurosurgery; Spine; Spine Arthroplasty Journal; *AAOS; ASTM; North American Spine Society; Spine Arthroplasty Society; Spine section of AANS/CNS. Dr. Mihalko—Aesculap/B.Braun; Saunders/Mosby-Elsevier;* Journal of Arthroplasty; *ASTM International.*

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AAOS *Now*
April 2013 Issue
http://www.aaos.org/news/aaosnow/apr13/research4.asp