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Trunnion Corrosion in Total Hip Arthroplasty – Basic Concepts

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Synopsis

There has been an increased interest in the role of corrosion in total hip arthroplasty. This is based on reports of early implant failures and adverse local tissue reaction resulting from excessive corrosion at the modular interfaces of some implant designs. Orthopedic alloys are not selected based solely on their mechanical properties of strength, but rather because they possess the best balance between material properties of corrosion resistance and mechanical properties of strength. The passive layer of a metal oxide that develops on a surface of a metal serves a critical role in preventing corrosion. However, this protective layer is a dynamic structure. Aggressive corrosion occurs on implants when the kinetics of this oxide layer's destruction dominates over its generation. There is a spectrum of different types of corrosion defined by the environment and stability of the passive layer. Pitting is the localized dissolution of this protective metal oxide film. Crevice corrosion occurs with a similar mechanism but in an isolated environment that promotes corrosion. Fretting corrosion or mechanically assisted crevice corrosion (MACC) occurs with the addition of mechanical oscillating loads at the modular junction that disrupts this protective layer. Understanding this process is important to improve implant designs, surgical technique, and assessment of patients.

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DISCLOSURE STATEMENT

None

Keywords

corrosion; trunnion; adverse local tissue reaction; total hip arthroplasty; head neck taper corrosion; passive layer

Introduction

Corrosion is electrochemical degradation of metallic materials, and has been a central problem of orthopedics since metals were introduced as implantable biomaterials [1]. In this text, metals (elements) and alloys (combinations of elements) will be called “metals”. As early as 1937, Venable, Stuck and Beach were the first to report that Vitallium, a cobalt chromium based alloy, was superior to other metals (e.g. aluminum, copper, iron, nickel, lead, gold, magnesium, silver, and iron based alloys such as stainless steels) in corrosion resistance, and had adequate mechanical properties required for an implantable medical device [2]. These early researchers observed the detrimental effects of corrosion on tissue, and thus how corrosion resistant alloys were paramount for orthopedic implants. This initial work set guidelines for the performance by which future metallic alloys were selected for use in hip arthroplasty and other types of implants. Since the introduction of modular hip implants in the 1960's, concerns regarding metal corrosion at these modular connections have been ever present [3]. These concerns were validated when galvanic, crevice, and fretting corrosion were observed and demonstrated in retrieved hip implants in the early 1990's [4]. Similarly, adverse tissue reactions such as fibrous tissue masses, now termed adverse local tissue reaction (ALTR) or pseudotumor, were associated with head-neck trunnion corrosion as early as 1988 [5]. The contribution of corrosion debris to the long-term performance of arthroplasty implants in general remains largely unknown.

Though metal-related tissue necrosis and implant revisions had been previously reported with historical metal on metal implants [6], there was an increase in metal-on-metal bearing use in the early- to mid-2000's when surgeons tried to address problems associated with conventional polyethylene wear. Adverse metal-associated tissue reactions then reappeared as a source of poor implant performance in some arthroplasty designs [7–10]. Research in this area led to improved diagnostic tools such as metal artifact reduction sequence (MARS) MRI [11], metal ion level tests [12], and metal hypersensitivity tests [13, 14]. Using these diagnostic tools, several investigations have noted that metal-associated tissue destruction, which was initially thought to be unique to metal-on-metal wear debris, could also be found in implants with metal-on-polyethylene bearings [15–19]. The degree to which these adverse local tissue reactions in metal on metal hip replacements were due to metal wear debris from the articulation or from modular taper junction corrosion remains uncertain [20, 21].

Because modularity is part of almost all modern total hip arthroplasties, it is important that orthopedic surgeons understand how corrosion at these interfaces can determine implant outcome. In this paper, we review the basic concepts of corrosion thermodynamics on implant surfaces, the role of passive oxide layers in protecting the metal implant surfaces from corrosion, the various types and mechanisms of implant associated corrosion, and how

these interact in the case of modular taper junctions to accelerate corrosion and decrease implant performance.

Corrosion Basic Science

Corrosion is driven by a material's "desire" to go toward a lower chemical energy state, and occurs when electrons flow from the anode (loss of electrons) to the cathode (gain of electrons). This is an exothermic process with minimal activation energy which allows the reaction to occur spontaneously at either a fast or slow rate. When a bare metal surface without a protective metal-oxide film is directly exposed to air or an aqueous solution, the reaction is explosively exothermic. An excellent example of this is titanium. Vacuum processed titanium powder corrodes from a metallic state to an oxide at such a violent rate and with such a powerful release of energy that it has been used as solid rocket propellant. On the opposite end of this spectrum, ASTM titanium alloys have such a low rate of corrosion that they are an ideal material for many types of orthopaedic implants. The difference in the rate of corrosion between vacuum processed titanium and ASTM titanium alloy is that ASTM titanium alloy rapidly forms a protective oxide film (also known as a passive layer) on its surface when it is exposed to oxygen. This process is known as "passivation". This protective oxide film nearly stops corrosion on the surface of the metal, making a metal that can be used as a rocket propellant safe and stable for use as an implant.

Corrosion occurs in three basic steps (Figure 1). First, metal from the surface dissolves into the aqueous environment and cations are removed (oxidation). Second, remaining electrons are attracted to a differential charge at another point on the surface. A current is generated as electrons are removed from the surface, driving the reaction (reduction). Finally, metal oxide or metal hydroxide form as byproducts. Metal oxides and insoluble metal hydroxides (rust) form an insulating layer on the metal surface. This precipitate forms a film that inhibits the kinetics of the reaction and insulates the metal from further corrosion [22].

The passive "chemically stable" metal oxide layer is the key to preventing corrosion on orthopaedic implants. As compared to metal hydroxide, the metal oxide is more stable, less soluble, and more insulating. Since the metal oxide film is non-conductive and an insulator, it prevents the flow of ions (current) from the solution's aqueous layer to the metal surface and thus limits the rate of corrosion. These films can only form with specific types of metal alloys. Stable passive metals include Ti, Cr, Ta, Nb, and Zr. Other metals such as Al, Cu, In, Tn can form metal oxide layers, but these protective layers can quickly dissolve in the presence of chloride ions, a main constituent of physiologic solutions. Remaining elemental metal in alloys can corrode to form a metal hydroxide layer (ie rust) which has a limited ability to prevent the movement of ions and limit corrosion.

Corrosion still occurs after passivation, but the passive film provides a large kinetic barrier slowing the speed of the reaction. The thermodynamics after passivation are changed because the activation energy is greatly increased with a passive barrier. This film forms almost instantly on the surface of the metal. If the film remains homogenous and undisturbed, corrosion is inhibited as the *uniform* passive film shields the metal surface from the aqueous reaction (Figure 2). Passive films prevent corrosion based on their properties such as thickness and stability. This layer is not static, and is in a constant steady state

equilibrium. Its thickness is a balance between reactions that erode and build the film, and a function of the voltage or electric field across the film and pH of the solution. A complete discussion of this is outside the scope of this discussion but reviewed [23].

Types of Corrosion

The basic types of corrosion that can occur on an orthopaedic implant include pitting, crevice, fretting and mechanically assisted crevice corrosion (MACC). These different types of corrosion are all part of continuous spectrum based on a metal alloys ability to avoid breakdown of the protective passivation layer. Pitting corrosion occurs from localized breakdown in the passive layer. Crevice corrosion is a form of pitting corrosion in a relatively harsher environment with limited mass transport. Fretting corrosion in a crevice is a form of MACC where crevice corrosion is facilitated by mechanical stress or mechanical motion. “Fretting” refers to low amplitude mechanical wear of a surface, “fretting corrosion” refers to low amplitude wear of a metal surface where passivation layer removal takes place increasing metal degradation, and “fretting corrosion in a crevice” is more simply referred to as MACC.

Pitting corrosion is due to a localized relative dissolution of the passive film (Figure 3). , i.e. where there is a small disruption on the passive film. This decreases the activation energy hurdle for corrosion, creating a more favorable environment for corrosion by speeding the kinetics in that area. Slight inconsistencies that develop and grow in the passive film lead to breakdown in small areas, which leads to the development of a focused anode, and localized galvanic corrosion [24]. For example, if one area of the passive film has a small amount of more permeable hydroxide than impermeable oxide, a defect can develop over this area of the passive surface (*pitting*). This creates a more permeable and less protective film. In aqueous solutions, halides (ie Cl-) are readily available that can also help dissolve oxides and encourage less of an oxide barrier to form, allowing a larger flow of metal ions to escape from this small disrupted area. As a consequence, a differential cathode can develop over a large distant surface in response to the point anode. This creates a large difference in potential charge at two distant points. The current flow between these two charges is similar to the voltage difference across a battery and similar to galvanic corrosion [24, 25].

Crevice corrosion occurs, as the name implies, in a crevice where there is limited diffusion of ions in and out of the local environment producing a harsher more corrosion inducing environment (Figure 4). Thus, as this crevice environment becomes more corrosive, compared to pitting corrosion, the activation energy is lower given the more favorable (e.g. acidic) local conditions. Reaction kinetics are increased, however the energy released (overall free energy) remains the same. The total hip arthroplasty trunnion is theoretically a closed environment that prevents ion diffusion (Figure 4). However, in practice, only a partial seal is established at a finite point on the neck-head taper connection, not across the entire taper surface. The trunnion occluded area becomes an obstacle preventing the diffusion of ions. Oxygen becomes depleted, limiting the ability of a passive layer to regenerate itself (repassivation). Hydrogen and chloride ion (hydrochloric acid) concentration increases. This creates a low acidic pH environment that accelerates corrosion by limiting repassivation. In this acidic crevice, the rate of corrosion is increased and the low

concentration of oxygen limits metal oxide formation as a passive film. Simultaneously, there is increased chloride concentrations that further helps increase the solubility of the passive film and decrease its stability. The resulting conditions in the trunnion crevice deteriorate to the points where the metal surface has a small inconsistent passive film that is not insulated from an aqueous solution. These are ideal conditions for corrosion.

As previously mentioned fretting corrosion in a crevice environment is considered and MACC, i.e. is combined crevice corrosion with additional mechanical disruption of the passive film with low amplitude wear (Figure 5). Tribocorrosion refers to the process of this combination of corrosion and wear combined [26, 27]. Physical shearing forces remove the protective passive film that serves as a barrier to corrosion for the metal surface. At the taper interface, small oscillations between the taper surfaces can act to remove passive film and thus cause significant fretting corrosion or MACC. Increased head sizes, smaller and more flexible trunnions, and smaller trunnion contact areas all act to increase the local shear forces across the taper junction and thus increase the potential for MACC. In the context of trunnion corrosion, both fretting corrosion and MACC are terms generally used interchangeably despite that fretting corrosion need not take place in a crevice environment.

Trunnion Corrosion

Trunnion design parameters play a critical role that contribute to passive film instability. A Morse taper is defined by the angle that the taper surfaces make relative to the longitudinal axis of the component [28]. These taper design parameters (length, slope, and angle) and the elastic modulus of the metal affect the overall structural rigidity. For example, for two theoretical trunnions of identical metal alloy, the trunnion with the shorter mating surface and narrow diameter will be the more flexible. Theoretically, this produces more fretting movement and consequent MACC. This has led to multiple groups suggesting that changes in trunnion geometry with smaller diameters and shorter taper length are important factors in predicting trunnion corrosion [29–33]. At what point these theoretical design parameters reach a threshold to make an implant more susceptible to corrosion in the highly complex in vivo environment remains unclear.

The magnitude of mechanical stress across the trunnion may also effect passive film stability. Larger femoral head diameters and longer neck length femoral heads may cause greater material deformation at the taper junction and thus more relative motion between the two mating surfaces. These clinical generalizations are evidence based on a series of retrieval studies that suggest larger head size are associated with increased incidence of ALTR [34–37]. Other models have suggested head-neck offset would increase micromotion [38]. Taper geometry and contact length are also known to play key roles in controlling trunnion corrosion. In vivo, the femoral head does not make contact with the entire mating surface of the femoral stem across the surface of the trunnion. Thus, the smaller the contact area, the more stress that would be placed across the trunnion surface. Further, there is variation in surface topology across different tapers [39] with some tapers having grooved surfaces while others having smoother surfaces. It is generally accepted that increased mechanical stress and movement across the trunnion interface due to various prosthetic design features will result in accelerated corrosion and an increase of ALTR [40, 41].

The stability of the passive film is essential to limit corrosion from the optimized highly corrosive environment. The oxide film that forms on the passive layer prevents the dissolution of the metal ions and can regenerate itself if disrupted. Tribiocrorrosion has the synergistic ability to accelerate corrosion from the mechanical wear across the passive film. Trunnion design parameters such as taper length, diameter, contact area, and mechanical stress across the trunnion interface may accelerate corrosion and lead to ALTR but the interplay of these factors, including surgical technique, remains to be determined.

Arthroplasty surgeons should be aware of these issues, and how to limit the possibility of corrosion. Modularity should be minimized where possible, especially if minimal or no advantages to wear or stability will result. Femoral head material can have an effect on the amount of corrosion that may occur at the taper, and, if possible and cost effective, ceramic heads should be considered [42]. During femoral head and trunnion assembly, care should be taken to make certain the trunnion is dry and void of any debris before assembly. While many manufacturers do not offer optimal assembly technique guides [43] it has been determined that an axially directed force of over 2.5kN should be utilized to optimize the modular connection between the head and trunnion of the stem [44]. When dealing with a revision scenario for a corroded trunnion, it has been shown that cleaning the trunnion and placing a new femoral head (CoCr or Ceramic) has no difference in stability of the head trunnion junction compared to pristine new tapers [45]. In a revision scenario for adverse local tissue reaction, ceramic heads should be highly considered. Surgeons should also make certain after they assemble the femoral head trunnion connection or after they implant total knee arthroplasty components that the bovie cautery should not be placed on or near the CoCr bearing surfaces. The plasma discharge can disrupt the oxide layer of the bearing and cause pits on the surface [46, 47]. These simple pearls can help surgeons optimize and reduce the risk of corrosion related factors to obtain the best environment and scenario for a good long-term outcome.

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Key Points

- The passive layer serves a critical role in preventing corrosion on orthopaedic implants.
- Orthopaedic alloys have not been selected because of the best mechanical properties (i.e. strength), but because they have the best corrosion resistance.
- The femoral head-neck trunnion creates an optimal environment for corrosion to occur because of the limited fluid diffusion, acidic environment, and increased bending moment.

Figure 1:

Corrosion on a surface. In theory, maximum corrosion occurs if the complete metal surface was exposed on a surface. Corrosion occurs in three basic steps: 1. Metal dissolves on the surface into the aqueous environment and cations are removed (oxidation). 2. Remaining electrons are attracted to a differential charge at another point on the surface where electrons are removed from the metal driving the reaction (reduction). 3. Metal oxide or metal hydroxide form as byproducts of this reaction. Metal oxides and insoluble metal oxides (rust) form an insulating layer on the metal surface almost instantly that inhibit the kinetics of corrosion and insulate the metal from further corrosion.

Figure 2:

Corrosion on a Surface with a passive film – Uniform Corrosion. If a passive film remains homogenous and undisturbed, corrosion is inhibited as the *uniform* passive film shields the metal surface from the aqueous reaction. Metal oxide forms a stronger barrier to migration of the positive charged metal and electrons as compared to the insoluble hydroxide (rust). The passive film thickness is a balance between reactions that erode and build the film.

Figure 3:

Pitting Corrosion. Slight inconsistencies that develop in the passive film lead to breakdown in small areas, development of a focused anode, and localized galvanic corrosion. A large flow of metal ions occurs at this focused anode. A differential cathode will then develop over a large surface at a distant point. The current flow between these two charges is similar to the voltage difference across a battery or galvanic corrosion.

Figure 4:

Crevice Corrosion. Pitting corrosion that occurs with limited diffusion of ions creates optimal conditions for corrosion. The total hip arthroplasty trunnion is a closed environment that prevents ion diffusion. A water-tight seal is established at a finite point on the neck-head taper and prevents the diffusion of ions. Oxygen depletion and a low pH environment prevent repassivation.

Figure 5:
Fretting Corrosion or MACC. A physical shearing force across the trunnion removes the protective passive film. This creates a larger surface for crevice corrosion to occur.