Modularity in Total Hip Arthroplasty: Benefits, Risks, Mechanisms, Diagnosis, and Management

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Abstract

Modular implants are currently widely used in total hip arthroplasty because they give surgeons versatility during the operation, allow for easier revision surgery, and can be adjusted to better fit the anatomy of the specific patient. However, modular implants, specifically those that have metal-on-metal junctions, are susceptible to crevice and fretting corrosion. This can ultimately cause implant failure, inflammation, and adverse local tissue reaction, among other possible side effects. Surgeons should be aware of the possibility of implant corrosion and should follow a set of recommended guidelines to systematically diagnose and treat patients with corroded implants. Ultimately, surgeons will continue to use modular implants because of their widespread benefits. However, more research is needed to determine how to minimize corrosion and the negative side effects that have been associated with modular junctions in total hip arthroplasty. [Orthopedics. 2017; 40(6):355-366.]

Total hip arthroplasty (THA) is one of the most prevalent operations in the world, with more than 1 million artificial hips being implanted annually. Total hip arthroplasty is often regarded as one of the most successful and cost-effective orthopedic procedures. Much of this success can be attributed to the modular designs that have become widespread in orthopedic surgery and provide important benefits to both surgeons and patients. However, in recent years, modularity has come under scrutiny due to the failure of dual modular femoral components and the prevalence of mechanically assisted taper corrosion. As a result, the necessity of modular designs is being questioned. This review will help explain the concepts of modularity and mechanically assisted taper corrosion in THA.

Benefits

Modularity in THA has significant benefits. Modularity reduces implant inventory and gives surgeons the ability to use different combinations of materials (ie, cobalt-chromium or ceramic) in the final assembled implant. Most important, modular designs give surgeons versatility when reconstructing the hip and allow for easier revision THA in the future if an osseointegrated implant needs to be altered. Implant stability and range of motion can be optimized by allowing surgeons to re-establish leg length, femoral anteversion, and femoral offset even after the final femoral component has been implanted. An example of the success of modularity on the acetabular and femoral sides is the ease of head and liner revision THA in patients suffering from osteolysis. In one study, 19% (19 of 100) of THAs re-
quired a change in the neck length after the femoral component was inserted to achieve leg-length equality, demonstrating the benefit and necessity of modularity.³ This intraoperative optimization of the reconstruction would not be possible with nonmodular implants.³

**DISADVANTAGES**

Despite the benefits of modularity, there are some significant drawbacks, such as early aseptic loosening, osteolysis, and radiolucent lines.⁷ Recently, modularity has been associated with mechanically assisted taper corrosion at modular junctions. Dual modular stem designs and other modular junctions are subject to corrosion and implant fracture. Adverse reactions to metal ions have been documented at the head–neck junction (also known as trunnion), neck–stem junction (also known as dual modular), and metaphyseal–diaphyseal junction. There is mounting evidence that modular designs, rather than the inherent characteristics of the material being used, cause corrosion.⁸⁻¹⁰

The negative effects of modularity in THA cannot be ignored. Manufacturers are reconsidering the current designs of the trunnion and dual modular junctions because of accumulating evidence that mechanically assisted taper corrosion may account for some proportion of device failures. Two dual modular femoral stem designs, ABG II and Rejuvenate (Stryker, Kalamazoo, Michigan), have been voluntarily recalled, and the Profemur Z (Wright, Memphis, Tennessee) was redesigned and remains under scrutiny due to its extremely poor clinical track record.¹⁰ These dual modular designs offer the benefits of a modular implant but are also associated with high rates of corrosion, early implant failure, and adverse local tissue reaction (ALTR). Pivec et al¹⁰ studied nearly 200 patients who had a THA using the ABG II design. They found that 2 years after THA, approximately 30% of the implants were corroded. According to the Australian Orthopaedic Association National Joint Replacement Registry, patients with the Profemur Z implant have a revision rate of approximately 10% after only a few years.¹¹

**Corrosion and Potential Risk Factors**

Cater and Hicks¹² first reported the corrosion of orthopedic implants in 1956 after observing a link between soft tissue damage and metal implants.¹ Corrosion can occur through five distinct mechanisms: galvanic,¹³ fretting,¹⁴ crevice,¹⁵ pitting,¹⁶ and intergranular.¹⁷ A thin layer of metal oxide covers the surface of metal implants in oxygen-rich environments, functioning as protection from further oxidative damage. This oxidized protective layer is produced by passivation (Figure 2). When damage occurs to this oxide layer, the surface metal of the implant reoxidizes (also known as repassivates) to reestablish the protective oxide layer. Corrosion occurs when the repassivation process is interrupted.¹⁸ Mechanically assisted corrosion, specifically via the mechanisms of crevice and fretting corrosion, is a significant problem associated with THAs. Collier et al¹⁹ sent questionnaires to 15 manufacturers of orthopedic implants and studied more than 600 modular hip implants. Combining the data from these two sources, they concluded that more than 30% of mixed-alloy head/stem junctions, less than 10% of titanium-alloy modular components, and less than 6% of cobalt-alloy devices are corroded.

Modular junctions are predisposed to crevice corrosion. At modular junctions machined with tight tolerances, such as the head–neck junction, the aqueous chemical environment of the body cannot fully penetrate the space between the two surfaces. The tiny gaps (or crevices) between the
two surfaces of the implant are in effect microisolated. A current runs between the cathode (the surface of the implant outside the crevice) and the anode (inside the crevice) because of the imbalance of oxygen, even if the individual parts of the modular junction are composed of the same metal (Figure 3). As a result, oxygen tensions fall at the anode, while the concentrations of hydrogen and chloride ions rise. In this oxygen-poor environment, the surface of the implant cannot repassivate; thus, crevice corrosion occurs. During this process, phosphate reacts with chromium ions to produce a black, tarry precipitate (ie, chromium III phosphate) on the surface of the implant and adjacent to the crevice (Figure 4). Consequently, serum studies will show a normal or only slightly elevated chromium level in patients whose implants demonstrate corrosion at modular junctions. However, cobalt’s high solubility results in elevated serum cobalt levels. Thus, a failing modular junction will exhibit differential elevation of serum cobalt several fold above that of serum chromium. In contrast, when metal-on-metal articulations fail, both serum cobalt and chromium levels generally rise, serving as a point of differentiation from corrosion that occurs at the site of modular junctions.

In addition to crevice corrosion, modular junctions are vulnerable to fretting corrosion as well. During the latter process, sites of contact between modular articulations experience surface pressure that gives rise to friction. Micromotion at modular articulations during mechanical loading generates this surface pressure, which can interfere with passivation and accelerate the release of metal ions, thereby enabling crevice corrosion. Of note, loosening of the implant is not responsible for the phenomenon of micromotion. Loading causes the various components
of the modular implant to flex at the slip region while remaining stuck together, creating fretting. The slip region is located at the interface of a modular implant where mechanical loading can cause micromotion, resulting in disruption of the passivation layer (Figure 5).

Subtle differences in the design and geometry of the taper, the combination of materials used in the implant, the mechanical environment, material performance, and the implantation time affect susceptibility to corrosion. In fact, since Morse tapers were introduced in THA 30 years ago, there has been no standardization among the device manufacturers.

It has become clear, however, that certain taper design characteristics increase the risk of corrosion. The most dramatic example is that corrosion is more frequent and robust at the neck–stem junction than at the head–neck junction. The 3-dimensional topography of trunnion surfaces varies and also affects corrosion. It was reported that 64% of the head–neck tapers from five different manufacturers had threaded, rough surfaces consisting of peaks and troughs that this topology was associated with increased corrosion. Similarly, manufacturing tolerances influence the amount of micromotion at the taper junction. Increasing values of angle tolerance are associated with increased micromotion on the male component of the trunnion, while off-axis loading causes the female component to dip in such a way that micromotion becomes substantially greater at one side of the female component than the other.

Goldberg et al., through a series of in vitro tests, determined that the flexural rigidity of a taper design has an inverse relationship with fretting corrosion. This observation explains why shorter taper lengths, in general, correlate with increased corrosion. Unfortunately, the current manufacturing trend is for trunnions to become less rigid over time. This trend is driven by a desire for materials that more closely match the elastic modulus of bone and reductions in the neck profile to help reduce dislocation events. Taper assembly appears to affect fretting. Assembling a taper in dry conditions does not prevent fretting or corrosion, but dry assembly does increase the amount of load needed to create micromotion. Kop and Swarts discovered that the longer the implantation time, the more likely corrosion is to occur. Gilbert et al. found that this relationship occurs because cyclic loading increases the corrosion rate regardless of other circumstances. In addition, they found that a larger femoral head offset (6 mm compared with 0 mm) increased the rate of fretting corrosion, as the offset head tends to rock and create more frictional torque compared with a neutral head, which pistons on the trunnion. Regarding modular materials, stainless steel femoral components and cobalt-chromium heads were much more susceptible to corrosion than modular implants made of only cobalt-chromium. It is unclear exactly why this is the case, but it likely has to do with the elemental composition of stainless steel. Ceramic heads produced significantly less corrosion than cobalt-chromium heads. Much of the existing literature indicates that a larger femoral head results in a decreased implant dislocation rate, although Jack et al. found that larger femoral heads resulted in a greater revision rate. Much of the evidence surrounding femoral head size and corrosion is conflicting as well. Some studies have found that serum metal ion levels do not change depending on the femoral head size, whereas other studies have indicated that there is greater corrosion at the head–neck junction with 36-mm femoral heads compared with 28-mm heads. It was suggested that during everyday activities, larger heads cause greater torque along the taper junction, resulting in increased micromotion between the neck and the head of the implant. One study identified that wear rates significantly increased if femoral heads were greater than 32 mm in diameter, whereas a separate study concluded that the ideal head size was likely between 28 and 32 mm in diameter.

Reaction to Metal Ions

Metal-on-metal articulations recently had a revival and began to replace metal-on-polyethylene articulations, which are susceptible to osteolysis and early aseptic loosening. However, although metal-on-metal articulations reduce volumetric wear (the debris generated during the wear of a bearing over the entire surface area of contact), corrosion can still occur at metal-on-metal junctions and metal ions can...
be released. In fact, there is evidence that the absolute number of wear particles has actually increased due to the minute size of metal wear particles.40-42

The metal ions that are released by modular implants—mostly cobalt and chromium but nickel as well—can modify cytokine expression, bind to cellular proteins or enzymes, and breach cell membranes, as well as cause fibrosis, necrosis, dermatitis, and vasculitis.43-45 For example, individuals with failed metal-on-metal articulations are more likely to have dermal hypersensitivity.46 Furthermore, an aseptic lymphocyte-dominated vasculitis-associated lesion (ALVAL) is present only in individuals with metal-on-metal implants that contained chromium, cobalt, and nickel.47,48

Cobalt and chromium are each toxic at high concentration. They act on local tissue near the modular implant and at distant sites in the body. Metal ions reach multiple sites throughout the body, including the bone marrow, lymph nodes, spleen, liver, and heart, via hematogenous or lymphatic transport.49,51 Specifically, the effect of chromium depends on its ionic valence. Hexavalent chromium is categorized as a group 1 carcinogen and can cause pulmonary epithelial cancer, yet trivalent chromium is much more benign.52 Merritt and Brown53 determined that hexavalent chromium is the predominant chromium ion released when corrosion occurs at stainless steel/chromium-cobalt alloy implants. Nevertheless, the trivalent chromium ion is often detected in the cells surrounding joint replacements because hexavalent chromium is quickly reduced to trivalent chromium in red blood cells.54 Cobalt ions from metal-on-metal implants impede osteoblast activity55 and modify lymphocyte function and chemokine secretion.56,57 They are furthermore associated with neurologic, thyroid, and cardiac dysfunction.58,59 Regardless, the metal ions released from orthopedic implants generate three principal hazards for human cells: genotoxicity, cytotoxicity, and hypersensitivity.

Genotoxicity. When the genetic makeup of a cell is damaged by genotoxic material such as cobalt or chromium, the long-term sequela of these alterations is cancer, which can occur even at concentrations previously considered to be sub-toxic.50,61 Through oxidative stress, cobalt and chromium disrupt DNA and damage tissue structure and function.62 Specifically, chromium releases free radicals that create breaks in DNA strands, while cobalt inhibits topoisomerase II and thereby handicaps DNA replication and damages DNA strands.63,64 Both cobalt and chromium ions suppress DNA repair pathways, leading to defective gene expression.65

Prior research has suggested that metal-on-metal articulations may raise patients’ risk of developing cancer or other genetic defects. One study, for example, reported that DNA synthesis declines when cells are exposed to chromium or cobalt.66 Dunstan et al67 furthermore found that the incidence of chromosomal aberrations was higher in individuals with modular THA implants than in individuals without implants. In fact, individuals with implants exhibited aneuploidy (abnormal number of chromosomes) 2.5 times more when compared with control implants, in addition to a 3.5-fold increase in the number of chromosomal translocations.68

Even so, the clinical implications of genotoxicity from modular hip implants remain uncertain. One study of more than 80 published articles examined the possible association between cobalt-chromium implants and the risk of cancer. It was concluded that the serum concentration of cobalt and chromium ions in individuals with metal-on-metal articulations was insufficient to dramatically elevate the risk of systemic cancer. This finding was supported by in vitro and in vivo assays demonstrating a low likelihood of additional DNA defects in the presence of physiologic cobalt or chromium ion concentrations that occur with metal-on-metal articulations. In 40 tumor bioassay studies, cobalt and chromium ion concentrations were elevated in patients with hip implants, but no study reported a significant increase in systemic cancer.69 A Finnish study, which examined 2000 patients approximately 15 years after a first-generation metal-on-metal articulation, also found no increase in the incidence of cancer, suggesting that other factors may be implicated in the development of cancer in this cohort.70 More recently, modern metal-on-metal articulations have also failed to manifest an increase in the probability of cancer.71 Finally, even if DNA damage may be correlated with the use of modular implants, it cannot account for an elevation in cancer risk because implant materials other than chromium and cobalt also accumulate DNA damage.69 Christian et al69 inferred that local effects such as inflammation, which occurs independently of specific implant material, may in fact provoke the observed changes in DNA of cells surrounding metal-on-metal articulations. Thus, despite the apprehension that cobalt and chromium ions may increase or accelerate cancer, existing research does not support such a conclusion.69

Cytotoxicity. Both cobalt and chromium ions are considerably cytotoxic, with cobalt being slightly more so. Even at lower concentrations, cobalt ions can prompt greater macrophage and lymphocyte death by a mechanism involving stimulation of tumor necrosis factor-alpha secretion and macrophage apoptosis.72-74 In fact, evidence from multiple in vitro studies indicates that even after incubating for either 24 or 48 hours, cobalt and chromium ions both lead to macrophage apoptosis.72 DNA laddering reveals that DNA fragmentation declines after 48 hours, likely indicating the presence of necrosis.72-74 Hypoxia appears to contribute to this process, as cobalt-chromium alloys can establish a hypoxic-like environment of greater oxidative stress for the periprosthetic tissue surrounding modular implants.75 The viability of histiocytes decreases by 97% in the presence of cobalt and chromium particles, while that of fibroblasts falls by 95%. In contrast, ceram-
ic particles decreased the viability of the histiocytes by only 18% and had little to no effect on fibroblasts, indicating that cobalt-chromium particles are significantly more toxic. A retrieval study supported these results by noting that necrosis and tumoral calcinosis-like reactions occurred in histiocytes containing metal ions.

**Hypersensitivity.** Hypersensitivity refers to an undesired reaction mounted by the immune system in response to an allergen. Also known as allergies, metal hypersensitivities comprise contact allergies to chromium, cobalt, or nickel. These reactions are prevalent in the general population. It is thought that metal allergies develop over time because of extended exposure to physical objects that include jewelry, cell phones, and clothing fasteners. The presence of such an allergy pertains directly to orthopedic procedures, given that implanting a metal hip in such a patient could induce adverse reactions (e.g., hives, eczema, redness, and itching). Nickel, for instance, is often an incidental component of the cobalt-chromium alloys that are used in orthopedic implants; it is also a more robust immunological sensitizing metal than either cobalt or chromium. An immune response can be elicited when these metal ions bind to circulating serum proteins, such as albumin, and form haptens. The metal-bound, denatured protein complex hapten serves as the critical trigger to initiate an immune response.

When an individual with a metal allergy is exposed to immunoreactive haptens that contain nickel, cobalt, or chromium particles, a hypersensitivity reaction ensues. Antigens activate T-cell delayed-type hypersensitivity lymphocytes, leading to cytokine release and macrophage mobilization. The subsequent hypersensitivity reaction can occur by one of two mechanisms—as an immediate humoral response or as a delayed cell-mediated response. Typically, those that result from orthopedic implants are cell mediated or, more specifically, a type IV delayed hypersensitivity. The T-cell delayed-type hypersensitivity lymphocytes, which are activated by haptenic antigens, are a category of CD4+ helper T-cell lymphocytes that are presented with a hapten to a major histocompatibility complex class II molecule. As a result of this interaction with major histocompatibility complex class II, interferon-γ is released and activates macrophages to secrete various cytokines, such as granulocyte-macrophage colony-stimulating factors, tumor necrosis factors, monocyte chemotactic factors, and migration inhibitory factors. Cytoxic T-cells are thus recruited and mediate the resulting type IV hypersensitivity reaction. An additive effect can be seen, as macrophages also activate T-cell delayed-type hypersensitivity lymphocytes, which then activate more macrophages, and so on. The result is an immunologic overreaction.

Of note, sensitivity to nickel in a patient may predict cross-reactivity to cobalt and chromium. Cross-reactivity occurs because the denatured carrier, rather than the metal or hapten itself, simulates a reaction. Nickel, cobalt, and chromium all denature carrier proteins by similar mechanisms and can thereby affect the immune system in an analogous manner. Thus far, it is unclear what the relationship is between metal implants and metal allergies. Various studies by Thyssen et al concluded that the revision rate following THA was similar in patients with and without metal allergies, indicating that metal allergies have little effect on the performance of a metal implant. Furthermore, in a case-control study, Thyssen et al observed that the prevalence of metal allergies was similar in dermatitis patients with and without metal implants. Various other studies have found that there is no increase in metal allergies following the implantation of a metal-on-metal articulation, and existing metal allergies do not result in implant complication. Thienpont and Berger even noted that a patient with serious metal allergies to chromium, cobalt, and nickel received a hip implant made of cobalt-chromium alloy and had no symptoms of metal hypersensitivity.

However, other studies contradict these data. Thomas et al and Hallab et al both found evidence of increased metal allergy in patients with metal-on-metal articulations. Furthermore, a separate study reached the conclusion that lymphocyte reactivity increases with metal exposure and increases even further with metal-on-metal articulation. Various case studies have also described individuals with metal allergies who have serious reactions after receiving a metal-on-metal articulation. Regarding these findings, it is unclear whether metal hypersensitivity occurs because of implant failure or the implant fails because of a preexisting metal allergy.

**Adverse Local Tissue Reaction**

Adverse local tissue reaction is a designation for the negative clinical manifestations that occur when implants corrode to produce metal wear debris and metal ions. Adverse local tissue reaction has been shown to contribute in cases of implant failure. Such a reaction may be suggested by pain in the groin, hip, thigh, or buttock. However, the relationship between ALTR and genotoxicity, cytotoxicity, and metal hypersensitivity is not yet well understood. Furthermore, another consistent finding across cases of ALTR is that patients are initially asymptomatic with well-functioning implants for the first 1 or 2 years; after this period, however, the symptoms of ALTR begin to emerge. If pain is present and persistent immediately after surgery, the patient is likely suffering from an infection or a loose implant rather than ALTR. When a patient has ALTR, magnetic resonance imaging (MRI) should show an enlarged capsule with fluid in the effective joint space, as well as dehiscence of the capsule and tendon inflammation. In addition, some patients with ALTR exhibit abductor muscle degeneration and bony erosion of the femoral neck. Nevertheless, ALTR sometimes goes unnoticed in patients. Fehring et al evaluated more
than 100 patients with modular THAs for ALTR and found that roughly a third of asymptomatic patients suffered from ALTR. This statistic is concerning, as many diagnostic and management algorithms are based on symptomatology.

The three main types of ALTRs are ALVAL, pseudotumor, and osteolysis. Aseptic lymphocyte-dominated vasculitis-associated lesions denote a periprosthetic inflammation reaction, which is accompanied by soft tissue necrosis, lymphatic infiltration, and abnormal joint fluid. In fact, this response is comparable to a type IV hypersensitivity reaction in the soft tissue surrounding metal-on-metal articulations.\(^\text{104,105}\) In one study of hip arthroplasty patients who required revision surgery because of implant failure, tissue samples showed perivascular infiltrates of T-cell and B-cell lymphocytes with accumulation of plasma cells and macrophages (Figure 6).\(^\text{106}\) Various studies have found that tissues involved in ALVAL contain lymphocytes that have increased metal ion content compared with tissues involved in ALVAL that contain macrophages.\(^\text{107,108}\)

Like ALVAL, pseudotumor may present with pain, nerve palsy, palpable mass, and spontaneous dislocation.\(^\text{109,110}\) However, with pseudotumors, the tissue lymphocyte infiltration and necrosis is much more extensive. Pseudotumors are large, cystic masses often observed in patients with ALTR as a result of modular hip implant corrosion (Figure 7). The estimated prevalence of pseudotumors varies widely among hip implant patients. According to Pandit et al,\(^\text{110}\) 1% of patients with metal-on-metal implants develop a tumor within 5 years. In contrast, a separate case-control study reported that approximately 60% of THA patients with metal-on-metal articulations develop pseudotumors adjacent to their implant.\(^\text{111}\) Another study noted that pseudotumors were found in 37% of asymptomatic patients.\(^\text{112}\)

The last type of ALTR is osteolysis, or the destruction of bone secondary to osteoclast resorption. Two reliable imaging signs of osteolysis are cystic bony lesions and radiolucent regions near the femoral calcar and acetabular components (Figure 8).\(^\text{113}\) Osteolysis may be associated with pain when bone loss attenuates implant stability; it may also be asymptomatic, leading to likely underreporting of its prevalence. Conversely, in Sweden, osteolysis was cited as the cause of 75% of revision surgeries for patients with metal-on-metal articulation.\(^\text{114,115}\)

**Diagnosis and Management**

Several orthopedic societies have created a diagnosis and management algorithm to provide structure for the systematic and efficient evaluation of patients with a metal-on-metal articulation or modular junction.\(^\text{102,116}\) Patients should be broadly tested for pain and function during a follow-up routine. If patients have a symptomatic implant, a thorough clinical history and physical examination should
be performed. The severity, duration, location, and temporal onset of pain are all helpful in making a diagnosis, and a physical examination could help determine if other problems (such as metal allergy) are contributing to pain. Pain in the hip or groin is often indicative of a symptomatic implant, and persistent pain or a recurrence of preoperative pain can be a result of ALTR.10,102 Patients should be evaluated for intra- and extra-articular causes of pain, and anteroposterior and serial plain radiographs of the hip should be obtained.102 The focus should be on identifying aseptic loosening or osteolysis, as well as signs of impingement. A cross-table lateral radiograph is also helpful to determine component orientation.102 Assessing range of motion of the hip joint is important, as crepitus and scar tissue can be common in postoperative patients. Ultrasound or metal artifact reduction sequencing (MARS) MRI should be performed to test for fluid or palpable masses. In addition, it is important to evaluate the neurovascular functionality of the patient’s limb.102 Periprosthetic joint infection should be considered as well, but white blood cell count, serum erythrocyte sedimentation rate, and serum C-reactive protein are generally poor diagnostic criteria for periprosthetic joint infection with a failed metal-on-metal articulation or modular junction. However, synovial neutrophil percentage appears to be an accurate indicator of infection in patients.117

Elevated cobalt and chromium levels should be considered strong markers for implant failure. However, metal ion levels also do not reliably predict the amount or extent of soft tissue damage.118 If a patient presents with fluid or soft tissue masses, revision surgery should be strongly considered, regardless of metal ion concentration. The exact level, sensitivity, and specificity at which serum cobalt and chromium become predictive of implant failure is unknown. In 2010, the British Medicines and Healthcare products Regulatory Agency issued a safety alert for chromium or cobalt levels above 7 parts per billion (ppb). However, the specificity was 89% and the sensitivity was only 52%, indicating that 7 ppb is not an accurate measure of implant failure.116 Hart et al119 performed a study to investigate the 7-ppb cut-off and found that cobalt and chromium levels of approximately 5 ppb, with a specificity of 63% and sensitivity of 85%, were optimal. Although elevated levels of metal ions in the body are a useful diagnostic test, other tests should be done to reach a decision about revision surgery. The patient should be evaluated for aseptic loosening, osteolysis, and acetabular component orientation. If these signs are present, revision surgery should be considered. However, if there is no evidence of osteolysis or appropriately oriented components, metal ion levels should be carefully monitored for approximately 6 months.102,116

Magnetic resonance imaging can be used to diagnose ALTR and pseudotumor formation (Figure 7). However, a normal MRI, metal artifacts exhibit intense, significant distortions that affect the image. Altering the matrix and bandwidth of an MRI will reduce the amount of metal artifact. Metal artifact reduction sequence MRI reduces 90% of the artifact from an implant.120,121 Metal artifact reduction sequence MRIs are less sensitive to metal artifacts and appear to be the best way to study metal implants. Sabah et al122 studied patients with painful metal-on-metal articulation. Using MARS MRIs, they found that these patients most often suffered from severe muscle atrophy and fluid collections, along with muscle edema and solid masses. It was concluded that MARS MRIs are useful in diagnosing symptomatic hips, although the evidence is less clear regarding well-functioning hips.122 Similarly, Hart et al111 studied patients with symptomatic and asymptomatic hips using MARS MRIs. They found that the prevalence of pseudotumors was virtually identical between the two groups, calling into question the necessity of MARS MRI and the importance of its findings.111 However, one study found that ultrasound might be effective in identifying soft tissue abnormalities surrounding metal-on-metal implants.123 It is thus possible that the presence of an abnormality on a MARS MRI or ultrasound indicates implant failure in a symptomatic patient or imminent failure in an asymptomatic patient.

**Revision Total Hip Arthroplasty**

Assuming the femoral component is well fixed and the corrosion is not severe enough to warrant stem removal, titanium sleeves are useful in revision THA for modular taper corrosion. A titanium sleeve provides an uncorroded surface for contact with the ceramic junction and compensates for some of the damage to the taper surface. Ceramic heads with a titanium sleeve, even if large in diameter, cause minimal corrosion at modular taper junctions.124 Outcomes of revision THA using a metal head or a ceramic head with a titanium sleeve have not been widely published, but preliminary reports suggest excellent results with titanium-sleeved ceramic heads placed on well-fixed stems with prior taper corrosion. However, the corrosive damage to the trunnion has already occurred, so mid- to long-term follow-up of titanium-sleeved revision THA for modular functional corrosion will reveal if continued fretting in the area of prior damage predisposes these retained stems to implant fracture. Additionally, how to clean the corroded trunnion, with a scratch pad or wet sponge, remains to be determined in clinical evaluation.

**Prophylaxis**

The use of a prophylactic ceramic femoral head to avoid taper corrosion at the head–neck junction is common with the exponential rise in ceramic head utilization.31,125 However, the cost-effectiveness of this practice is unclear. Data emerging from multiple practices suggest the rate of head–neck taper corrosion is low (approximately 1% to 5%). It remains unclear if the additional expense of a ceramic head
justifies the widespread migration of surgeons to ceramic femoral heads.

**Conclusion**

Modularity in THA provides enormous benefit to surgeons and patients. It has become a staple in orthopedic surgery that is here to stay. Mechanically assisted taper corrosion at modular junctions is a cause for concern. For now, surgeons should take steps to reduce the adverse effects of modular components, and if implant failure occurs, surgeons should follow the emerging algorithm to treat patients as effectively as possible.

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