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Retrieval analysis of motion preserving spinal devices and periprosthetic tissues

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Abstract

This article reviews certain practical aspects of retrieval analysis for motion preserving spinal implants and periprosthetic tissues as an essential component of the overall revision strategy for these implants. At our institution, we established an international repository for motion-preserving spine implants in 2004. Our repository is currently open to all spine surgeons, and is intended to be inclusive of all cervical and lumbar implant designs such as artificial discs and posterior dynamic stabilization devices. Although a wide range of alternative materials is being investigated for nonfusion spine implants, many of the examples in this review are drawn from our existing repository of metal-on-polyethylene, metal-on-metal lumbar total disc replacements (TDRs), and polyurethane-based dynamic motion preservation devices. These devices are already approved or nearing approval for use in the United States, and hence are the most clinically relevant at the present time. This article summarizes the current literature on the retrieval analysis of these implants and concludes with recommendations for the development of new test methods that are based on the current state of knowledge of in vivo wear and damage mechanisms. Furthermore, the relevance and need to evaluate the surrounding tissue to obtain a complete understanding of the biological reaction to implant component corrosion and wear is reviewed.

Keywords: Dynamic motion preservation; Artificial discs; Retrieval analysis; Explant analysis; Polyurethane; Ultra-high molecular weight polyethylene; PU; UHMWPE; Mechanical testing; Chemical analysis; Histology; Wear particles wear debris

Motion preserving spinal implants have recently emerged as a new technology for the treatment of a range of degenerative disorders in the cervical and lumbar spine. In contrast with the historical paradigm for spinal implants, which was predicated upon static, load sharing fusion devices, motion preserving designs must not only share load but also restore motion to a diseased functional spinal unit. As a field, motion-preservation treatment of the spine remains in its infancy, and consequently, has the opportunity to benefit tremendously from the widespread practice of retrieval analysis.

Indeed, before clinical use of new motion preserving designs in humans, it is essential that the implants be exhaustively tested in the laboratory. However, because many motion-preservation designs and their biomaterials are novel, and without clinical precedent, it may be challenging for bioengineers to develop test methods that accurately predict their in vivo performance. Furthermore, prior to initiating a clinical trial, it is often impossible to anticipate the complete spectrum of clinical failure modes for a particular implant system, especially when no clinical experience is available to guide engineering judgment. Clinical failure of implant procedures may involve a variety of patient-, surgeon-, and implant-related factors. However, certain unusual clinical failure modes occur as a result of a unique combination of patient-, surgeon-, and implant-related factors, and, because of their rarity, may escape detection in a clinical trial. For this reason, the Food and Drug Administration (FDA) is keenly interested in the detailed

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analysis of explanted implants, as evidenced by the inquiry and recommendations of 3 FDA panels for cervical and lumbar artificial discs between 2004 and 2007. In the 2007 FDA panel meeting for the Bryan cervical disc, one of the conditions for approval was that the manufacturer conduct a 10-year postmarket retrieval analysis of the device (http://www.fda.gov/cdrh/meetings/071707-summary.html). Thus, retrieval analysis is not only considered an absolutely essential companion activity for prospective, randomized clinical trials, but also for the post-market surveillance of new spinal implant designs.

So what, then, is retrieval analysis? Retrieval analysis is the study of explanted devices and tissues for the purposes of understanding the implant in vivo performance. The implants and tissues are typically obtained during revision surgery, and are often helpful when attempting to determine the reasons underlying the failure of a particular surgical procedure. To gain an understanding of clinical failure modes of a particular device and its biomaterials, a detailed analysis of revision retrievals is absolutely essential. However, the extrapolation of such findings to patients who are not revised (ie, with well-functioning implants), can be problematic. For this reason, it may be desirable to study autopsy-retrieved implants and surrounding tissues. On the other hand, for motion-preserving spine implants with an elective patient population ranging in age from 18 to 60, it is simply not practical to expect a significant number of autopsy retrievals during an investigator's professional career.

Given the strong regulatory and societal implications, retrieval analysis is not merely an academic endeavor. Retrieval analysis is performed by clinicians, engineers, and biologists. There are great advantages from their collaboration as a team, which allows for the relevant patient-, surgeon-, and implant-related factors to be considered in as broad a context as possible. When properly performed by experienced investigators, retrieval analysis can provide a definitive source of information on implant and biomaterial-related failure modes, biocompatibility, and their impact on the overall longevity of the surgical procedure. When compared against the findings of experimental or numerical studies, the results of retrieval analysis can help validate preclinical testing and computer-based methods that are essential when evaluating new designs. Taken one step further, when the aggregate results of retrieval analysis are integrated into the implant design process, the technique can provide feedback or motivation for adjusting implant designs or the selection of alternative biomaterials. As explained in a recent NIH consensus statement:[1] "Technology progresses by facing its failures and learning from its successes. The goal of device research and development is to improve patient care through improvement of implants. A fundamental objective is to understand successful implants and assess failures through retrieval analysis."

In addition to the scientific motivation, there are also strong educational and ethical reasons for participating in retrieval analysis. When involving researchers, engineers, and clinicians in the early stages of their careers, retrieval analysis has a major educational component. Arguably, clinicians who are actively implanting motion preserving devices have an ethical responsibility to contribute to retrieval analysis to provide their patients with the best care possible. The removal of an implant, especially a lumbar artificial disc, potentially involves a heroic surgery by the physician. More importantly, it exposes the patient to increased risk of serious and potentially life-threatening complications. Thus, the clinician has a responsibility to ensure that implanted and explanted devices and tissues are properly analyzed and the results disseminated to stake holders. To be sure, there are many scientific, educational, and ethical reasons why implant designers, surgeons, researchers, and bioengineers are motivated to participate in retrieval analyses. These reasons have been touched upon in previous review articles and book chapters. It is a testament to the varied and compelling motivations for retrieval analysis that it continues to play an important role in the evolution of implant technology.

In this review, we summarize the literature on retrieval analysis of motion-preserving implants and conclude with recommendations for the development of new test methods that are based on the current state of knowledge in spine wear mechanisms. In addition, we provide support for coupling these analyses with the evaluation of periprosthetic tissues to determine the biological responses to the various implant designs. At our institution, we established an international repository for motion preserving spine implants in 2004. Our repository is currently open to all spine surgeons, and is intended to be inclusive of all cervical and lumbar implant designs, such as artificial discs, and posterior dynamic stabilization devices. Many of the examples in this chapter will be drawn from our existing repository of metal-on-polyethylene, metal-on-metal lumbar TDRs, and polyurethane-based dynamic motion preservation devices.

Practical aspects of retrieval analysis

Retrieval program

A retrieval program may be organized as the collection and analysis of implants from a single institution or from a multi-institutional study, or the program may be established independently as a more generalized retrieval repository. When a retrieval program is established as part of a clinical study, institutional review board (IRB) approval, or the equivalent, should be obtained along with the informed consent of each patient to participate when appropriate. A clinical study-type design is preferred when detailed clinical information, including protected health information, is being collected and analyzed as part of the study. Details on the design and establishment of a retrieval or repository program have been outlined previously.[2]

To ensure adequate receipt and processing of the retrieved implants, standard precautions are to be used when

handling the explanted components until they have completed a cleaning protocol. This may include keeping the implant components in appropriate chemicals to preserve adhering tissue, provided that the preservative does not degrade the component itself. At our center, implants fabricated from Ti alloy, CoCr alloy, and polyethylene are ultrasonically cleaned in soap and deionized water, rinsed, and sterilized using a 10% Clorox bleach solution. We omit the bleach solution for cleaning stainless steel implants, as there is the potential for corrosive attack with these alloys. Likewise, a mild cleanser is used for implant components comprised of polymers that may be vulnerable to chemical changes from the bleach solution. Furthermore, staff members affiliated with the retrieval program at our institution have completed the appropriate training in biohazard safety. Additional guidance for handling of retrieved implants and tissues may be found in ASTM Standard F561.[3]

The actual analysis of retrieved implants and tissues may involve a broad range of test methods, which are comprehensively described in ASTM Standard F561. This manual provides guidance for analysis of all implant components, including metallic, polymeric, and ceramic materials. Although a detailed summary of this standard falls outside the scope of this chapter, in subsequent sections we highlight specific test methods that have been particularly helpful in the characterization of retrieved metal-on-polyethylene and metal-on-metal disc replacements.

Wear and damage assessment

Because wear and damage of retrieved total disc replacements can occur at length scales that are not visible with the naked eye, microscopy may be necessary to identify damage modes. An optical stereomicroscope, with 10–40 times magnification, is typically sufficient to identify worn regions of retrieved implants, but it is frequently helpful to analyze the wear surfaces using scanning electron microscopy, which can achieve magnifications of 5,000 times or greater. In addition to optical and scanning electron microscopy, MicroCT and white light interferometry are methods that have proven particularly useful in our previous analyses of wear in retrieved total disc replacement components.[2,4,5] These novel wear assessment methods for disc replacements are highlighted in this section.

MicroCT analysis

We have used a MicroCT to nondestructively detect surface and internal voids and cracks within retrieved polyethylene total disc replacement components[4] and polyurethane spine motion preserving implants.[6,7] Depending upon their thickness, CoCr alloy components produce substantial artifacts in the MicroCT. The radiographic wire marker in the Charité (DePuy Spine, Raynham, MA) design, for example, also produces artifacts in the MicroCT that complicate interpretation of geometry at the rim. Consequently, we have found it helpful to remove the wire marker prior to MicroCT analysis of rim wear in that design. The wire marker artifact does not extend into the central core of the implant; therefore, if the scope of the analysis is restricted to dome wear, removal of the wire marker may not be necessary. For polymer components that do not incorporate wire markers (eg, the Prodisc [Synthes, West Chester, PA) or Dynesys (Zimmer Spine, Minneapolis, MN]), microCT artifacts are not an issue.

At our institution, polymer components of spine motion preserving implants are scanned at 18-μm voxel resolution using a commercial microCT scanner (μCT80, Scanco, Switzerland).[4] The 3-dimensional reconstructions of the component and 2-dimensional sections taken through the component are evaluated for the presence of surface, through-thickness, and internal cracks. We have previously observed the trajectory of cracks in polymer components of spine motion preserving implants, including the Dynesys.[6,7] Using optical microscopy, we have also characterized permanent deformation and wear patterns of polymer components from spine motion preserving devices. Using these methods we have been able to distinguish these forms of surface and sub-surface damage from iatrogenic damage that occurs during implant removal.

Because of attenuation artifacts encountered with metallic components, as discussed previously, microCT is only useful for polymeric components. To measure the macroscopic surface geometry of metallic components, coordinate measurement machines (CMM), laser profilometers, and optical profilometers are among the tools employed by the research community. To measure microscopic changes in the implant surface, white light interferometry may be used. As discussed below, interferometry is applicable to both metallic and polymeric components for disc replacement.

White light interferometry

At our institution we utilize white light interferometry (WLIR) to characterize the microscopic surface morphology of retrieved disc arthroplasty components. WLIR is capable of detecting surface height changes that are on the nanometer-length scale by measuring the interference of white light reflected off the component within a specified field of view, as compared with the light from a reference beam. We have successfully analyzed the wear surfaces of polyethylene and CoCr alloy total disc replacements at our institution using a NewView 5000 equipped with advanced texture analysis software (Zygo, Middlefield, CT).[5] We sample 5–10 square regions (typically 0.54 x 0.72 mm) of a component to obtain representative surface topography of the retrieved implant in both worn and unworn locations.

Figure 1 illustrates the surface topography obtained from the unworn and worn surface regions of a retrieved polyethylene disc replacement component. The unworn polyethylene surface is dominated by machining marks that are on the order of several microns in amplitude (Fig. 1, left).

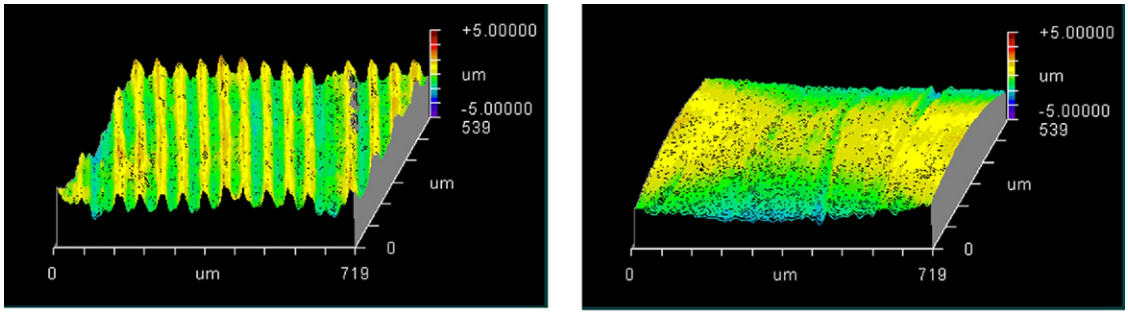

Fig. 1. White light interferometry images of an unworn (left) and worn (right) polyethylene implant surface.

Initially, microscopic evidence of adhesive/abrasive wear is detected by the erosion and removal of machining marks, along with the presence of fine scratches (Fig. 1, right).

The surface topography of a retrieved CoCr alloy disc replacement is shown in Figure 2. The unworn CoCr surface is usually relatively flat and featureless, aside from microscopic scratches generated during the final polishing stage of the manufacturing process (Fig. 2, left). In a region of wear, the CoCr surface has evidence of localized, microscopic scratches with a characteristic length scale that is larger than the residual features from polishing (Fig. 2, right).

As demonstrated in Figures 1 and 2, surface characterization using white light interferometry provides useful information about the wear mechanisms in total disc replacements. Furthermore, by quantitatively analyzing the surface data, the roughness and waviness can be quantified and compared with as-manufactured components, thereby providing insight into the magnitude of surface changes that occur in vivo.[8–10] Ultimately, quantitative measurements of implant surfaces are used to validate in vitro and computational models that seek to simulate in vivo wear processes.

Wear and damage mechanisms

As discussed in the previous section, retrieved components from spine motion preserving devices —whether metal-on-polyethylene or metal-on-metal—should be evaluated both macroscopically and microscopically for the presence of damage modes typically observed in large joint arthroplasty components (eg, burnishing, abrasion, scratching, pitting, plastic deformation, fracture, fatigue damage, and embedded debris). An exhaustive and detailed description of wear and wear mechanisms is beyond the scope of this paper, as it is already contained in entire books dedicated to this subject.[11] Furthermore, a generic guide for the analysis of retrieved components is summarized in the Appendices for ASTM Standard F 561.[3] Consequently, this section is intended to provide the reader with a concise summary of the most relevant wear and fatigue damage modes that may be encountered when inspecting retrieved spine motion preserving implant components.

Abrasion and scratching

Abrasive wear, evidenced by scratching, is common to both metallic and polymeric components for total disc replacement. Abrasion may occur macroscopically and be apparent to the naked eye, or it may only be apparent when viewed using microscopy. Abrasive wear occurs when microscopic surface irregularities (also referred to as “asperities”) in an implant scratch the surface of the opposing counterface. In the case of metal-on-polyethylene, the asperities on the metallic implant produce scratches in the softer polymeric implant. In the case of CoCr alloy metal-on-metal implants, abrasive wear is produced by locally stiffer asperities, such as carbides, plowing through the relatively softer cobalt alloy matrix. Abrasive wear can also occur when softer polymeric

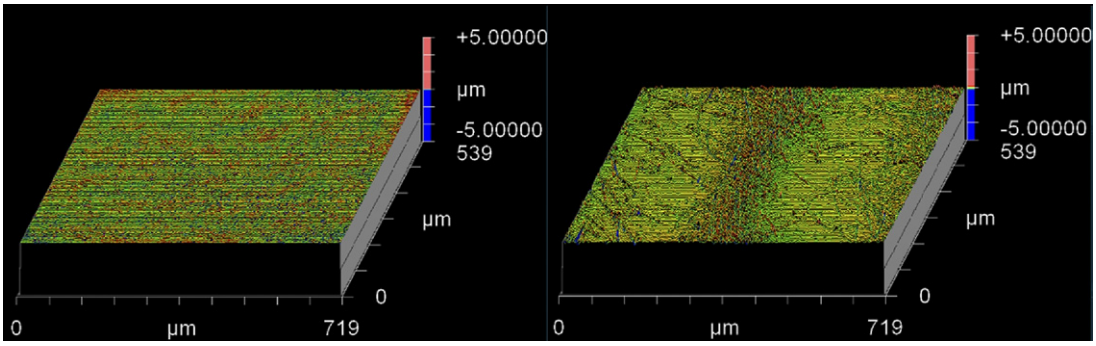

Fig. 2. White light interferometry images of an unworn (left) and worn (right) metal-on-metal implant surface.

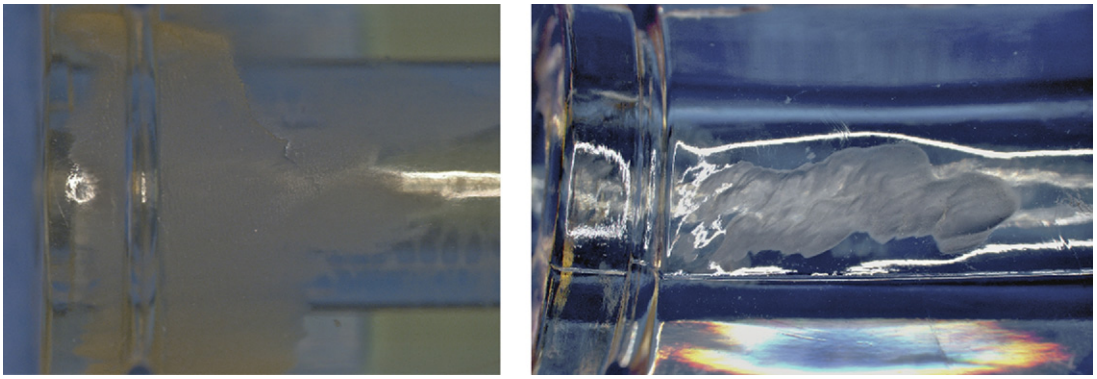

Fig. 3. Abrasive wear observed on polymeric components from retrieved Dynesys systems, implanted 1.1 (left) and 1 (right) years.

components of the implant contact surrounding bony structures (Fig. 3).

During retrieval analysis, the pattern of scratches on an implant, whether macroscopic or microscopic, provide clues to the kinematics (motion) of the surfaces while they were contact in vivo. The microscopic multidirectional scratches and crisscrossing wear paths at the dome of a retrieved polyethylene TDR (Fig. 4) are consistent with the type of microscopic abrasive wear mechanisms previously observed in retrieved hip replacement components.[12,13] By matching comparable regions of damage on 2 opposing bearing surfaces, it is further possible to infer the orientation of the components while they were in contact.

Burnishing

Typically encountered with polyethylene disc components, burnishing gives the polymer surface a polished, glossy appearance (Fig. 5). At a microscopic length scale, burnishing is associated with an adhesive wear mechanism, whereby the polyethylene surface wear occurs by adhesion to the metallic counterface. Highly magnified images of a burnished wear zone from a retrieved total disc replacement are shown in Figure 5, and as noted also show evidence of scratching which denotes the presence of abrasion. For this reason, the dominant wear mechanism in metal-on-polyethylene articulations is considered to be a combination of adhesion and abrasion, as seen in total joint replacements.[12,13]

Regions of burnishing on polyethylene retrievals may be appreciated with the naked eye under the proper lighting conditions. In contrast, the bearing surfaces of retrieved

Fig. 4. Microscopic, multidirectional scratches and crisscrossing wear paths at the dome of a retrieved polyethylene total disc replacement that was implanted 6.2 years.

Fig. 5. Burnishing observed on the dome of the polyethylene component of a retrieved total disc replacement.

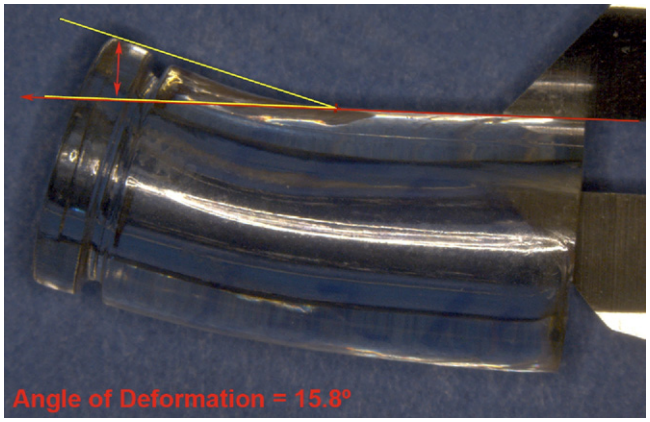

Fig. 6. Polycarbonate urethane component of a retrieved Dynesys system that was implanted for 1 year, demonstrating evidence of permanent bending along the length in response to off-axis compressive loading.

metallic components are typically highly polished after removal from the body. Therefore, burnishing on a metal-on-metal disc replacement that occurred in vivo is very difficult to discern without the aid of scanning electron microscopy.

Surface deformation

Surface deformation, sometimes referred to plastic deformation or creep, corresponds to permanent changes in the shape or geometry of a total disc replacement without the loss of material. Although surface deformation is not considered a wear mechanism, it could represent an undesirable damage mode. When permanent changes in the geometry of a device compromise its in vivo function or kinematics, surface deformation is considered a failure mode for the implant.

In spine motion preserving devices, macroscopic surface deformation has been observed in components that undergo compression in vivo. Polycarbonate urethane spacers used in the Dynesys system undergo deformation due to cold flow of the material, the compressive load applied during the surgery and subsequent loading in vivo, which results in permanent bending of the implant and indentations from the supporting polyaxial screws (Figs. 6 and 7, respectively). Additional deformation of soft polymer components may occur from interaction with other components from the implant; eg, the cord component that passes through the center of the polyurethane spacer in the Dynesys system (Fig. 7).

Fatigue wear and fracture

Fatigue wear and fracture, especially of the rim, are a concern with polyethylene TDRs. David et al.[14] have reported a case in which the entire rim of a disc replacement fractured from the central body of the core after 9.5 years in vivo. This case of rim failure was attributed to severe oxidation degradation following gamma sterilization in air.

The severity and clinical manifestation of fatigue-related rim damage in the Charité design varies widely, ranging

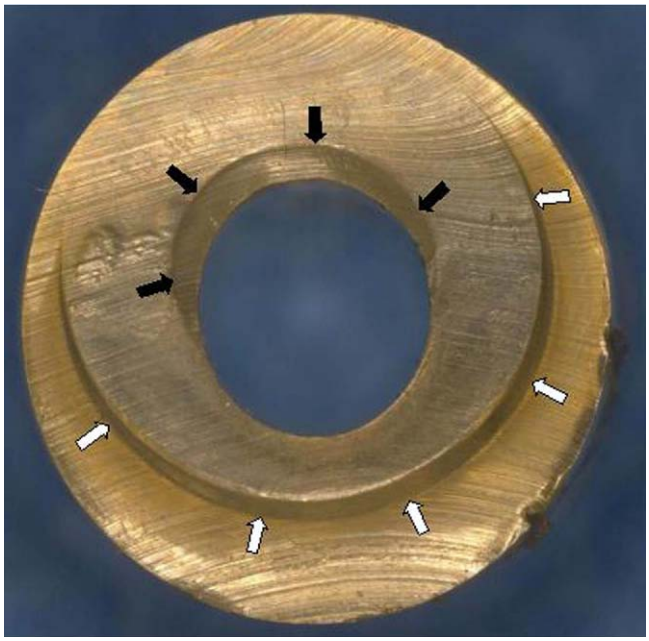

Fig. 7. Indentations observed in the spacer component from a retrieved Dynesys system that was implanted for 1.9 years. *Black arrows* denote deformation from the cord, while *white arrows* indicate deformation from the supporting pedicle screw.

from full-thickness rim fracture (Fig. 8) to more benign radial crack formation (Fig. 9). In our retrieval studies of the Charité, radial cracks have been observed in 19 out 38 implants examined thus far.[15] Similarly, transverse cracks have been observed in 14 out of 38 retrieved implants.[15] In most cases, fatigue fracture is related to impingement by the metallic endplates. Fractures have also been observed in polymer components of posterior devices such as the Dynesys (Fig. 10).

The etiology and incidence of fatigue wear and fracture

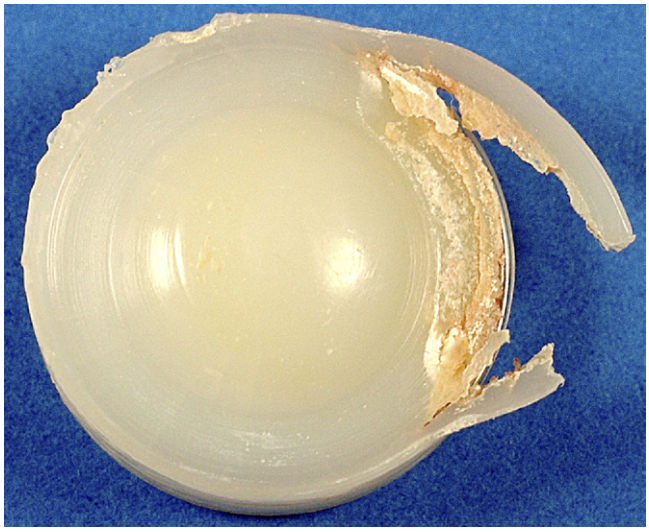

Fig. 8. Fatigue-related full-thickness rim fracture observed in a retrieved Charité implant that was implanted for 16.1 years.

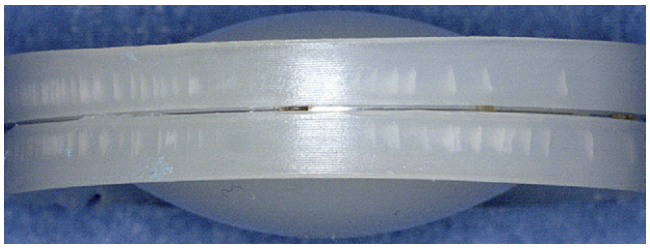

Fig. 9. Fatigue-related radial rim cracking observed in a retrieved Charité prosthesis that was implanted for 5.3 years.

in TDR remains unclear, as it may require many years for progressive fracture mechanisms in a particular design to result in clinical symptoms. It is further unknown what role gamma sterilization in air, or in a low oxygen environment, has on the fracture mechanisms in disc replacement. These research topics are currently under investigation at our institution.

There have been no reports of fracture of a metal-on-metal disc replacement component in the literature. Similarly, implant fracture has not been a clinical concern for contemporary metal-on-metal bearing surfaces in hip prostheses.

Embedded debris

Embedded debris is an unusual but noteworthy damage mode for disc replacements. We have observed embedded debris in which a fractured radiographic wire marker became trapped between the rim and a metallic endplate (Fig. 11). The clinical significance of this wear mode is unknown

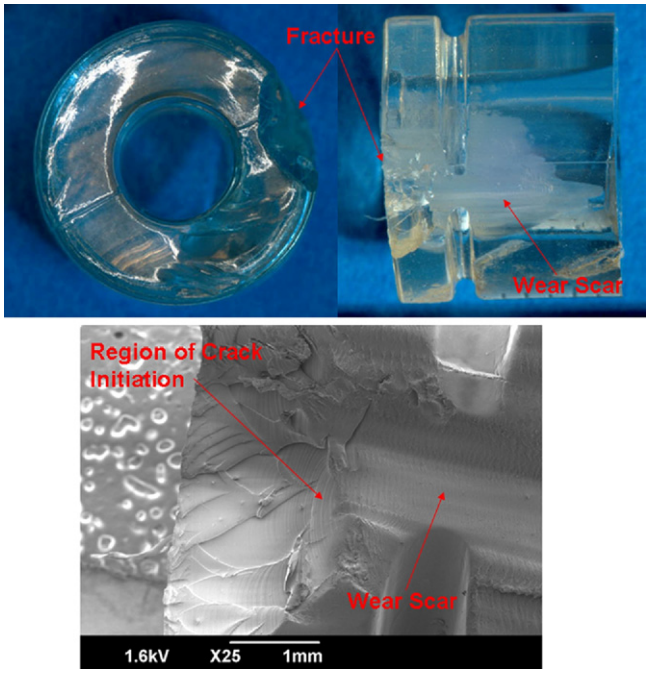

Fig. 10. Optical microscopy and SEM analysis of a fatigue-fractured spacer from a retrieved Dynesys system that was implanted for 1.1 years.

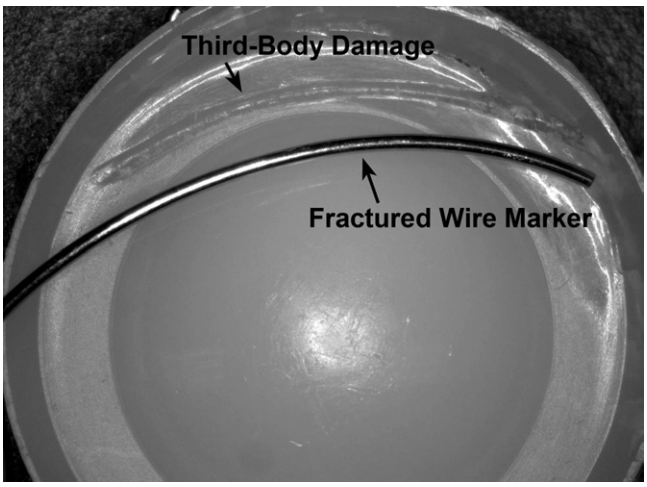

Fig. 11. Third-body damage caused by a fractured radiographic wire marker in a 12.7 year implanted component, which depicts rim damage in the polyethylene core.

at the present time. In large total joints, embedded debris is a potential roughening mechanism for the metallic component, which can result in accelerated wear. Such a mechanism was not apparent in the retrieval shown in Figure 11, which appeared to be relatively stationary and resulted in only a faintly perceptible indentation of the metallic endplate. As a result, additional retrievals are necessary to better understand the incidence and clinical significance (if any) of embedded debris in total disc replacements. Although metallic surfaces are also theoretically susceptible to embedded debris, including third-body scratching by the radiopacifiers contained in bone cement for total joint applications, there are no reports yet in the literature of third-body wear being observed in metal-on-metal disc replacements.

Chemical changes in vivo

Although characterization of wear and damage mechanisms is perhaps one of the most fruitful goals of retrieval analysis, it is also equally important to investigate whether the biological environment has resulted in any long-term chemical changes to the implant material, whether it be composed of polymer, metal, or ceramic. With polyethylene components, in vivo oxidation may be a potential long-term damage mechanism for artificial discs[4]; however, in vivo chemical changes to implants may be incidental and unrelated to clinical performance. For example, for polyethylene acetabular components, severe rim oxidation has been shown to occur after 10 years in vivo[16]; but the clinical relevance is unclear because these implants do not normally articulate at the rim. With polyethylene TDR components, rim failure has been observed to occur in vivo, but it is unclear if oxidation is the driving mechanism in all of these cases or whether impingement alone may be sufficient to generate the types of fractures that have been documented to occur clinically.[2] In polycarbonate urethane components,

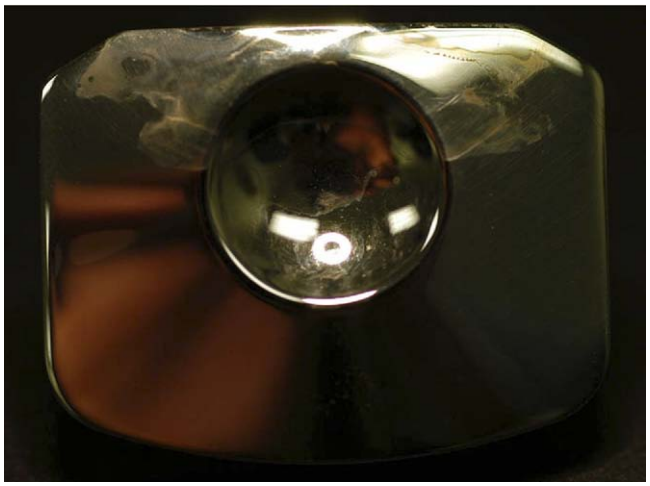

Fig. 12. Biofilm observed in CoCr alloy, metal-on-metal total disc replacement.

surface chemical changes associated with polyurethane degradation have been observed; these changes were only associated with implants that have been implanted for relatively long periods of time and primarily in regions where the implant was exposed to biological fluid.[7,17] Trommsdorff et al. reported that chemical changes in retrieved Dynesys polycarbonate urethane spacers were negligible at 100 μm below the surface.[18] The clinical relevance of these surface chemical changes remains unknown.

In vivo changes in chemistry may also occur with metallic components. In metal-on-metal hip implants fabricated from CoCr alloys, tribochemical deposits have been observed on the surface of retrieved implants.[19] These carbon and oxygen rich surface layers, which have a smoky or hazy appearance, are attributed to joint fluids which become fused to the bearing surface. The biofilms are thought to have a beneficial effect, by providing a solid lubricant for the articulating surface. We have observed comparable biofilms on retrieved CoCr alloy, metal-on-metal disc replacement components (Fig. 12), suggesting that a similar mechanism may be occurring.[20]

A wide range of well-established techniques has been developed to assess chemical changes in polyethylene and metallic components for spine motion preserving implants; a comprehensive list is provided by ASTM F561. With polyethylene components, the preferred methods include characterization of crystalline content using differential scanning calorimetry, measurement of oxidation using Fourier transform infrared spectroscopy (FTIR), and measurement of mechanical properties using the small punch test (ASTM F 2183). In previous case studies of polyethylene disc replacements, both FTIR and the small punch test have been successfully employed.[4,14]

For metallic components, electron dispersive x-ray spectroscopy (EDS), in combination with scanning electron microscopy (SEM), is useful for characterizing the chemistry of the alloys and biological surface layers. As previously alluded to, we have successfully employed EDS to analyze biofilms on the surface of retrieved metal-on-metal implants fabricated from CoCr alloys.[20] These EDS analyses have enabled us to confirm that carbon- and oxygen-rich tribochemical reactions can occur on both the concave and convex sides of metal-on-metal articulations in the spine. Further studies with an additional number of retrieved implants are necessary to determine the incidence of biofilms on CoCr alloy implants, as well as for disc replacements produced from stainless steel or metallo-ceramic alloy composites.

Analysis of retrieved tissues and particles

Extensive research on total joint replacements has revealed that the generation of polymeric and metallic wear debris from implant components are found in tissue surrounding hip and knee implants.[21–28] These submicron and micron-sized wear particles stimulate what is referred to as a foreign body reaction.[21] This reaction involves the activation of cells within the tissue, such as fibroblasts, and the infiltration of inflammatory cells, predominantly phagocytes. The phagocytic cells found within the tissue are generally macrophages and multinucleated giant cells.[21] Phagocytosis of the foreign material by fibroblasts and macrophages leads to cellular activation and the release of pro-inflammatory cytokines, including interleukin-1 (IL-1), interleukin-6 (IL-6), and tumor necrosis factor-α (TNF-α). These cellular mediators act in a paracrine and autocrine fashion to activate fibroblasts and inflammatory cells in the tissue. As a result of this response, a foreign body granulation tissue develops. This tissue tends to be fibrotic, but can undergo additional changes including apoptosis, necrosis and heterotopic ossification.[29–33] An infiltration of lymphocytes and plasma cells has also been observed in some tissues.[21] All of these histopathologic changes in response to wear debris can lead to tissue dysfunction, osteolysis, and implant loosening, and may contribute to the development of pain.[24] In the following sections of this review, we summarize the recent literature on the histological assessment of periprosthetic tissues and wear particles from motion preserving implants in the spine.

Histological assessment

Because nonfusion spinal implants have articulating components, there is the risk of wear particle generation from the bearing surface, which could lead to inflammatory reactions that have been well documented in the large joint orthopedic literature.[34] Even if the motion preserving implant does not include a bearing surface, surface fatigue, unanticipated impingement with adjacent bone, metal ion release, and leachable constituent extraction are all potential mechanisms for stimulating an adverse biological response. For example, the Acroflex was a one-piece artificial disc design that, over several generations of design spanning the

Fig. 13. Retrieved Acroflex.

1970s–1990s, included various formulations of silicone and vulcanized rubber. For each iteration of these experimental polymeric biomaterials, surface fatigue and in vivo degradation resulted in the generation of particulate debris that stimulated focal osteolysis, loosening, and ultimately implant failure (Fig. 13). In vitro testing was unable to identify the risk of an adverse tissue response to the biomaterials used in the device, and it was not until the implants were used clinically (in several iteratations) that this became apparent. This experience underscores the importance of developing an improved understanding of periprosthetic tissue response to wear and debris particles in the spine community.

Both spinal instrumentation for fusions, as well as motion preserving implants, are now well recognized to generate metallic and polymeric wear particles.[35–37] The long-term consequences of such particle generation, both in the posterior soft tissues of the spine as well as in the intradiscal space, remain poorly understood. Generally, an adverse cellular response to wear debris results in the infiltration, maturation, and activation of monocytes in periprosthetic tissue. However, the available information about the host response to contemporary polymeric and metallic artificial disc replacements indicates that, at least in the short term, inflammation in the surrounding tissue is limited in reports of animal models and human explants.[37–40] For metal-on-metal disc prostheses, the localized biological response to metal debris does not typically result in a significant infiltration of monocytes nor a metal sensitivity/allergic reaction.[41] The immunohistologic response to large numbers of metallic particles is an occasional macrophage and giant cell formation.[42] However, the detection of increased cobalt and chromium ions in the serum of patients receiving metal-on-metal TDRs suggests that a systemic response may occur.[43] The concern with metallic debris is the long-term biological effects, including harmful effects on immunity, reproduction, the kidneys, developmental toxicity, the nervous system, and carcinogenesis.[43–45]

For fusion implants, a study of the inflammatory response and osteolysis within the interior of retrieved titanium mesh cages showed particulate debris and macrophage infiltration in some cases, but there was never any evidence of osteolysis.[46] So, despite the presence of wear debris, the inflammatory response appeared to be greatly reduced when compared to hip or knee replacements. This was not true in another study examining unspecified regions around spinal fusion devices, where the incidence of osteolysis resulting from an inflammatory reaction to titanium and stainless steel wear debris was observed in 11 of 12 patients.[35]

From our own studies, we have observed early tissue responses after a lumbosacral disc replacement with a ProDisc-L implant, which was removed 14 months after implantation.[4] Micro-computed tomography of the tissue showed the presence of third-body debris, which consisted of bone fragments and metal. Histological analysis of the tissue showed several regions of increased fibroblast numbers and vascularization. Other areas of the tissue showed evidence of cell degeneration, and several fields contained fibrocartilage. No inflammatory cells were observed in areas where PE wear debris was found, although the amount wear debris was limited.

In contrast, in a study of retrieved tissue from 4 patients who had undergone revision surgery 6.5–12.8 years after receiving Charité TDRs, we observed many inflammatory cells, which consisted of macrophages and giant cells, within the fibrotic tissue.[48,49] The presence of giant cells was associated with ingested PE particles. Additionally, the inflammatory cytokines TNF-alpha and IL-6 were detected in macrophages and giant cells within the tissue. One patient showed signs of osteolysis of the sacrum.[49] These findings point to the complexity of the wear debris interactions in the spine over time, and of the clinically relevant wear debris required to stimulate inflammatory cell infiltration.

Wear particle assessment

The biological response to PE wear debris is mediated by a variety of specific particle characteristics, including wear volume, size, and shape. Studies have shown that exposure to PE wear debris within a specific size range results in enhanced macrophage activation in vitro.[50,51] In particular, submicron debris has been implicated as a potentially important contributor to the onset of osteolysis in failed total hip and knee replacements.[22,52,53] Others have also shown the importance of wear volume as a major contributor to the onset of osteolysis.[54,55] One in vitro study revealed a positive correlation between elevated PE particle volume and the subsequent production of tumor necrosis factor (TNF-α), IL-6, and IL-1β cytokine release.[54] A separate evaluation of clinical data showed that patients revised for osteolysis consistently had PE particle quantities on the order of 10 billion particles per gram weight of tissue, suggesting the existence of a threshold for the onset of osteolysis.[54,55]

Specific wear morphologies can also instigate a pronounced biological response in periprosthetic tissue.[29] To investigate the effect of particle shape, Yang et al.[56] injected globular and elongated PE debris into air pouches on the backs of mice.[29] Particles with large aspect ratios were

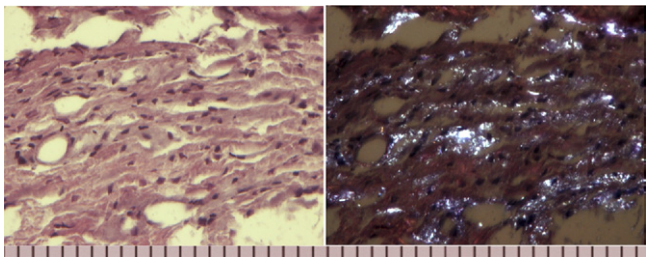

Fig. 14. TDR tissue sections stained with hematoxylin and eosin and imaged with brightfield (left) and polarized light (right) microscopy. The polarized image is of tissue retrieved at the time of revision surgery (9.2 yr) from a patient who received a pre-1998 Charité TDR implant. The PE debris is white and the score is 3 (range, 0–3). Scale interval represents 0.01 mm.

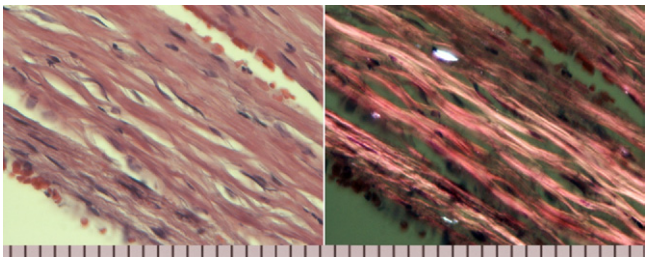

Fig. 15. TDR tissue sections stained with hematoxylin and eosin and imaged with brightfield (left) and polarized light (right) microscopy. The polarized image is of tissue retrieved at the time of revision surgery (2.2 yr) from a patient who received a post-1998 Charité TDR implant. The PE debris is white and the score is 1 (range, 0–3). Scale interval represents 0.01 mm.

shown to activate higher levels of TNF-α and IL-1β relative to globular particles with similar surface area. Similar findings have been reported by others.[22,57] These findings collectively support the dependence of a biological response to PE wear as a function of particle size, quantity, and shape.

In addition to PE wear debris, metal wear debris is found within the periprosthetic tissue of total hip joint replacements.[41,58–66] Larger particles are taken up by phagocytosis. Nanoparticles of metal debris and metal ions can be generated by wear and surface corrosion.[43] Nanoparticles are taken up by endocytosis or pinocytosis rather than phagocytosis, which may change the cellular responses to this type of wear debris. Metal ions of cobalt, titanium, and chromium have all been detected in solution during corrosion of metal alloys.[44] These metals exist predominantly as metal oxides and hydroxides. In addition, metal phosphates may also form in non-synovial environments of spinal tissue. The biological response to metal ions can result in cellular toxicity, and an allergic reaction to metal ions has been observed in some patients after total knee or hip replacement.[21]

Interestingly, for total disc replacements the in vivo wear rates appear to be less than in vitro simulated wear.[38,67] As such, the generation of wear particles is minimized, although it accumulates over time in the surrounding tissue.[20]

In a more recent study, we collected periprosthetic tissue from patients who had received new and old generation Charité TDRs. Prior to 1997, the Charité discs were sterilized in air, after which a first-generation, air-impermeable, polymeric barrier package (gamma sterilized) was used. The purpose of our study was to compare in the context of sterilization method PE wear particle volume in periprosthetic tissues taken at the time of revision surgery.[68,69] Periprosthetic tissue samples were collected from patients; 4 pre-1998 (implantation time 6.5–16.2 years) and 4 post-1998 (implantation time 2.2–8.1 years).

Tissue particle load was scored in 5 images from 0 (none visible) to 3 (elevated load, N $\geq$ 100), and the 5 scores summed. Tissue PE particle volume for pre-1998 TDRs (Fig. 14) was significantly greater than post-1998 TDRs (Figs. 15 and 16) (Student t test, $P < .001$). Tissue samples were also collected from 4 pre-1998 uncemented total hip arthroplasty (THA) implants (average implantation time: 14.2 years; range, 9.6–18.9) that were revised for wear-mediated osteolysis and aseptic loosening. PE particle load for pre-1998 TDR implants was comparable to pre-1998 THA implants, suggesting similar component wear. This study is the first to demonstrate a particle load comparison between periprosthetic tissues from TDR with different sterilization methods and THA historical implant cohorts. However, the relative long-term effects of the post-1998 are unknown, and await the availability of retrieved components and tissues.

Review of the literature on retrieval analysis

At present, the literature regarding retrieval analysis of motion preserving implants includes conference abstracts, individual case studies,[4,14,47,49] but relatively few published journal articles with larger series.[5,15,70] In this section, focus is put on studies that have included the analysis of a retrieval collection to seek commonalities in implant performance. Journal articles, as well as recent studies from conference proceedings, are included in this review of retrieval analyses for motion preserving implants. Because the conference proceedings may not be readily available to all

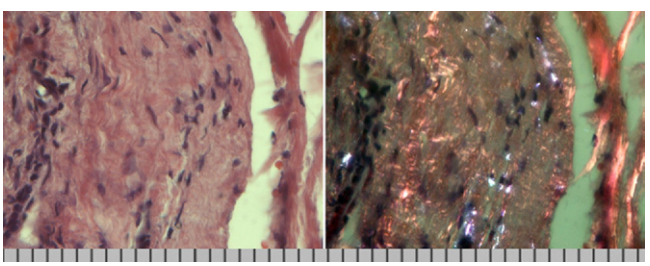

Fig. 16. TDR tissue sections stained with hematoxylin and eosin and imaged with brightfield (left) and polarized light (right) microscopy. The polarized image is of tissue retrieved at the time of revision surgery (2.2 yr) from the same patient (Fig. 15) who received a post-1998 Charité TDR implant. The PE debris is white and the score is 2 (range, 0–3). Scale interval represents 0.01 mm.

readers, details have also been provided about the findings from conference abstracts.

Cervical spine TDRs

The first published study in the field of artificial disc retrieval analysis was by Anderson et al. who examined short-term, retrieved cervical disc replacements of 2 designs: the Bryan and the Prestige (Medtronic, Memphis, TN).[70] The Bryan artificial disc is a 1-piece design consisting of 2 titanium alloy shells articulating against a mobile polyurethane core. The endplates are connected by a polyurethane sheath. The Prestige design consists of 2 stainless steel endplates that articulate with a ball-in-trough mechanism. Both the Bryan and Prestige designs are fully described in a recent book chapter.[71] In the clinical study, the 6 Bryan retrievals were implanted on average 11.8 months (range, 4–16), and the 2 Prestige retrievals were implanted from 18 and 39 months.[70] Few details about the retrieval methodology are included in this study; but it appears that microscopic characterization and the case of the Bryan disc, FTIR and GPC, were also performed. No significant changes in the FTIR or GPC results were detected relative to unimplanted controls, but this is hardly surprising given the generally short-term nature of the explants and the small sample size. As the first retrieval study of its kind in the field of disc arthroplasty, the work of Anderson and coworkers highlighted the importance of explant analysis for members of the spine surgeon community. However, because of the relatively small numbers of retrievals and brief in vivo exposure, no conclusions can be drawn about generality of their findings.

Jensen reported the bone ingrowth into the titanium shells of Bryan retrievals from 2 patients who were revised after 8 and 10 months of implantation.[72] New bone growth was observed into the porous coating of all 4 retrieved endplates. The mean bone ingrowth, quantified by histologic sectioning, was 30.1% (12% SD), which compared favorably with bone ingrowth reported in the literature for hip and knee replacements.

Recently, a retrieval study was presented at the 2007 Spine Arthroplasty Society in which the wear patterns in the core and sheath of the Bryan artificial disc were characterized.[73] A secondary goal was to evaluate whether formalin storage could adversely affect the explants. Researchers tested the hypothesis that height loss of the core would increase with implantation time. Height loss was measured in the cores of 17 Bryan cervical TDRs that were retrieved from 14 patients (5 male, 7 female, 2 unknown) after 1.6 years in situ (0.3–6.1 years). Implants were revised between 2003 and 2006 due to unresolved or recurring neck pain or radiculopathy (n = 15) and for infection or trauma (n = 1 each). Eight explants were stored in formalin for 1.4–3.3 years. Virgin, never-implanted sheaths and cores served as controls. Scanning electron microscopy and white light interferometry were performed to identify wear mechanism(s). The nominal height loss of the explanted cores (mean ± SD) was 0.22 ± 0.09 mm (range, 0.04 to 0.35). Although localized, microscopic evidence of adhesive and abrasive wear (confirmed by SEM and interferometry) was observed, researchers attributed the majority of initial height loss to creep as opposed to material removal because the initial glossy surface finish of the cores was generally well preserved, even after 6.1 years in vivo. The sheaths typically showed evidence of folding or permanent deformation in regions where the core made repeated contact. No correlation was observed between core height loss and implantation time ($\rho = 0.4$, $P = .18$). No significant height difference was observed attributable to formalin storage. However, macroscopic changes in the explant surface, including cracking, occurred after 3 years of formalin storage; these findings were not present at the time of explanation. Researchers observed minimal wear and nominal changes in core height (~0.2 mm) in this large series of PU cervical disc explants. However, marked surface changes were noted after exposure of explants to formalin and revising surgeons were cautioned to preserve PU explants in a formalin-free environment.

The short-term in vivo wear performance of stainless steel Prestige cervical total disc replacements (TDRs) has been characterized and compared with simulator results in two recent conference abstracts.[74,75] In a preliminary study, the early wear tests by Anderson et al.[70] were shown to produce similar wear mechanisms as retrievals; however, in the more recent study, the abrasion was more severe than what was observed in vivo.[74] Because available Prestige retrievals were implanted short-term, researchers conducted a second study to characterize the short-term wear response within the first 1.0 million cycles.[75]

At the 2008 meeting of the Orthopedic Research Society, researchers presented the results of 3 Prestige ST cervical TDRs that were wear tested in accordance with ISO/FDIS 18192.[75] To evaluate the short-term in vitro wear behavior of the Prestige ST the simulator was stopped after 0.05, 0.1, 0.2, 0.3, 0.4, 0.5 and 1.0 million cycles and interval analyses performed. These analyses consisted of photogrammtery and surface interferometry. The in vitro results from each interval analysis were compared to a Prestige ST retrieval collection analyzed from 9 patients (2 female and 7 male). The artificial discs were either Prestige I (n = 2); Prestige II (n = 2); or Prestige ST (n = 5) and were all of a stainless steel ball and trough design. The components had a range of implantation times from 0.7 to 3.3 years. Each component was previously characterized using the same methods as were used for in vitro interval analyses.

After 0.1 million cycles, the Prestige components exhibited a faint wear scar, produced by abrasive wear.[75] This wear mechanism was consistent with short-term explants. The average surface roughness of the worn regions for both the retrievals and in vitro tested components was measured to be 0.12 ± 0.08 μm and 0.16 ± 0.07 μm. The results of this Prestige retrieval study suggest that the ISO/FDIS

18192 standard test method replicates the in vivo wear patterns in TDRs after less than 1 million cycles of testing. This is in light of previous wear test methods that have shown other in vitro methods with up to 20 million cycles, which generated much more severe abrasive scratches than seen in vivo.[70,74] The data also suggested that the same mechanism of abrasive wear is occurring at the bearing surface of both the retrievals and in vitro-tested components, although the greater worn surface area in the wear-tested components may indicate that the ranges of motion are more extensive than those experienced by TDRs in vivo.

Lumbar spine TDRs

Fixation, wear, and in vivo degradation are key functional aspects of lumbar TDRs that have been evaluated in recent retrieval studies. Most of the retrieval research published to date for lumbar TDRs has been related to the historical Charité, manufactured by Link between 1989 and 2004 (this device is currently produced by DePuy Spine). A few retrieval studies have been published related to the ProDisc-L. Much less published retrieval data are currently available for metal-on-metal lumbar discs as compared with metal-on-polyethylene.

With regard to fixation, bone on-growth surfaces for TDRs have been tested in primate studies; but the fate of the bone-implant interface of lumbar TDRs in human patients has not yet been reported in the literature. Bone on-growth could theoretically complicate revision. In an abstract presented at the 2006 Spine Arthroplasty Meeting,[76] researchers investigated the failure modes, bone-implant interface, and extent of remaining CaP coating in retrieved Charité TDRs with textured endplates. Eight textured endplates from 4 explanted TDRs were studied following 3–6 years in vivo. In each case, the coated endplates were revised in straightforward fashion by an osteotomy adjacent to the implant. None of the endplates had evidence of residual CaP, and 1 endplate had adherent bone visible ($<$ 10% of the surface area) on optical microscopy. The bone on-growth to the textured surfaces was judged to provide improved resistance of the prosthesis to shear forces, which can result in migration when the teeth are not securely engaged in this design. Based on their findings, the authors advocated the use of textured, coated endplates over smooth endplates for total disc arthroplasty. Bone on-growth has also been visually observed on the titanium-plasma spray coating of retrieved ProDisc endplates.[47,77]

Analysis of wear and surface damage in long-term implanted Charité total disc replacements has been reported in a series of journal publications.[2,5,15] In the latest update of this multi-institutional series, 38 Charité components were retrieved with up to 16 years of implantation.[15] The components were revised for intractable pain and/or facet degeneration. Components were analyzed using optical microscopy and MicroCT. Forty-three percent (15/35) of components analyzed using MicroCT displayed 1-sided

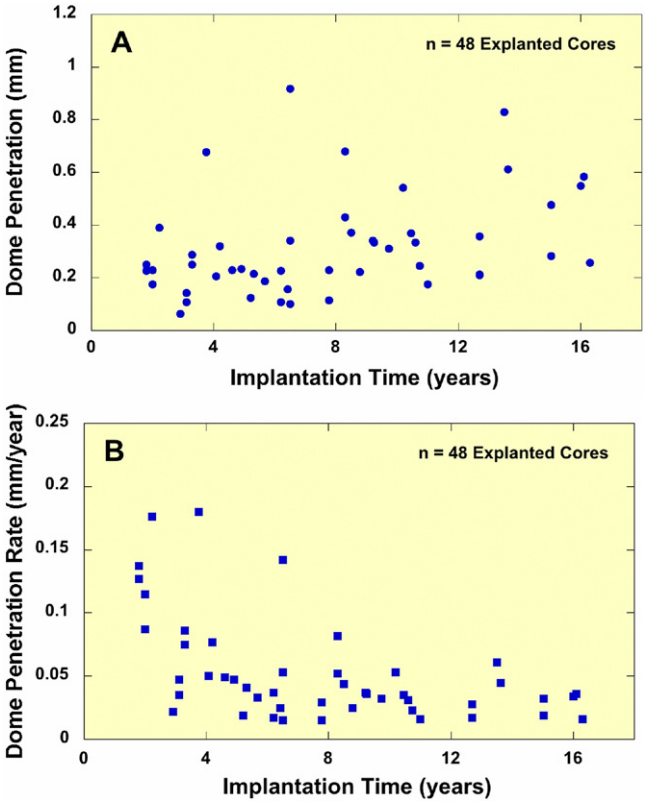

Fig. 17. A significant correlation was observed between implantation time and (A) penetration (Spearman's Rho = 0.42, p = 0.003) and (B) penetration rate (Spearman's Rho = −0.53, p = 0.0001) in retrieved Charité implants. (Adapted with permission.[15])

wear patterns.[15] Significant correlations were observed between implantation time and penetration and penetration rate (Fig. 17). The dome of the components typically exhibited burnishing, which was consistent with the multidirectional wear observed in hip replacements, whereas the rim frequently showed evidence of radial and transverse cracking (19/38 and 14/38 retrievals, respectively), often produced by impingement. The rim damage modes of plastic deformation, delamination, and cracking were similar to those associated with knee components. The published Charité retrieval literature provide crucial long-term in vivo wear data for validation of spine wear simulators, as well as for in vitro biomechanical testing.

Evidence of dome burnishing, as well as rim impingement, has also been noted in a recent conference poster summarizing a collection of 5 short-term ProDisc-L prostheses, implanted up to 2.2 years.[77] The bearing surface of the ProDisc-L showed burnishing (3/5 implants) mild scratching, and pitting (3/5 implants). Impingement was noted in 3/5 components and associated with burnishing and plastic deformation. The authors of the ProDisc retrieval study remarked that, "a potentially worrisome finding is the evidence of impingement. Whether caused by patients achieving a larger range of motion that the implant is designed to accommodate or by component positioning that allows impingement at even smaller range of motion, im-

pingement can be problematic."[77] A detailed example of a TDR retrieval study for the ProDisc-L, displaying mild anterior impingement, has recently been reported as a case study by Choma et al.[47]

Although rim impingement has been observed in retrieved TDRs of different designs, the clinical consequences of chronic rim impingement remain poorly understood. In a study presented at the 2008 Spine Arthroplasty Society meeting,[78] a retrieval collection of polyethylene mobile bearing TDRs was analyzed to determine whether rim impingement adversely affected dome penetration. 28/40 (70%) of retrieved cores, implanted for 2–16 years (7.9 years average), were classified as exhibiting chronic rim impingement based on observations of plastic deformation, burnishing, and/or fracture of the rim. Dome penetration was comparable in chronically impinged cores (average: 0.3, range, 0.1–0.9 mm) as compared with nonimpinging cores (average: 0.3; range, 0.1–0.5 mm). Rim penetration was significantly greater in chronically impinged cores ($P < .05$). Using linear regression, the dome penetration rate for cores with negligible impingement (0.036 mm/year, 95% CI: 0.012 to 0.061 mm/year) appeared slightly higher than in cores with chronic impingement (0.021 mm/year, 95% CI: 0.005 to 0.038 mm/year); however, the difference was not significant. Thus, the results of this study did not support the hypothesis that chronic rim impingement would be associated with greater dome penetration. However, the findings would suggest that dome wear and impingement are effectively decoupled phenomena, and may be studied independently of each other.

In addition to impingement, rim damage observed in polyethylene TDR retrievals has also been associated with postirradiation oxidation.[79] Analysis of explanted Charité cores using Fourier transform infrared spectroscopy has shown that the exposed rim experiences severe oxidation after 10 or more years.[79] These findings appear consistent for TDRs that were gamma irradiated in air, as well as in first-generation polymeric barrier packaging.[79] However, the central dome appears to somewhat protected from in vivo oxidation due to contact with the metallic endplates. No correlation was observed between wear of the central dome and oxidation.[79] These observations are similar to the in vivo oxidation patterns noted in artificial hips, which exhibit rim embrittlement after 10 years in vivo, but show reduced oxidation at the bearing surface where the femoral head contacts the polyethylene.[80] Unlike in hip replacement, the rim of a TDR core may be intended to support chronic loading for the lifetime of the patient. The findings of in vivo oxidation in gamma sterilized polyethylene TDR components provide additional motivation for developing in vitro mechanical tests that incorporate accelerated aging, or some other oxidative challenge, to simulate changes in the bearing materials that may occur with long-term in vivo exposure.

A recent study presented at the 2008 Spineweek meeting was conducted to better correlate long-term clinical wear rates of the Charité with simulator wear rates.[81] It was hypothesized that the wear mechanisms of the retrievals would be more accurately simulated by ISO protocols with coupled motion, as compared with ASTM-type protocols that resulted in linear motion. Researchers analyzed dome wear rate and surface morphology of 41 Charité (SBIII) explants from 35 patients (71% female). The cores were implanted for 7.5 years (range, 1.8–16.3). Twelve Charité wear-tested cores and 6 controls were also examined. Six cores were tested according to an ASTM-type protocol for 10 million cycles[82]; 3 additional cores were unloaded and soaked. Six cores were tested according to the ISO protocol for 2 million cycles with 3 loaded and soaked controls. All of the cores in this study were produced by the same manufacturer (Link, Germany). The explanted cores typically exhibited burnishing or evidence of adhesive/abrasive dome wear, consistent with multidirectional motion. The wear rate of the explants, obtained by correlation of dome height with implantation time, was 0.023 mm/year. The ASTM-tested cores exhibited unidirectional abrasive wear at a rate of 0.007 mm/Mcycles. The ISO-tested cores exhibited regional burnishing and wear at a rate of 0.124 mm/Mcycles (Fig. 18). Thus, the ISO protocol generated wear surface morphology that was closer to the retrievals than the ASTM-type protocol, and 1 million cycles of the ISO protocol corresponded, on average, to about 5.6 years of clinical wear. The findings from this study further suggest that the ISO protocol provides a useful starting point for clinical validation of spine wear simulations incorporating lumbar polyethylene TDRs.

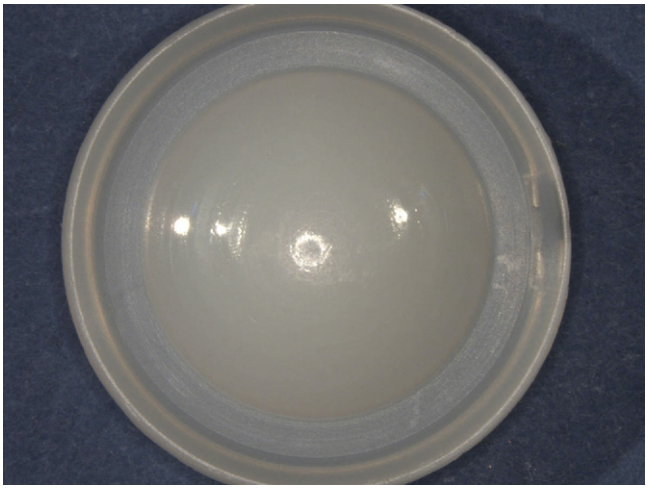

Fig. 18. Charité components tested using ISO wear testing protocols incorporating coupled motions exhibited regional burnishing and wear at a rate of 0.124 mm/Mcycles.

Because of its longer clinical history, more retrieval research has been published to date with metal-on-polyethylene lumbar discs than with metal-on-metal. At present, detailed results are available regarding the retrieval analysis of a single lumbar metal-on-metal total disc replacement.[83] This implant was removed after 12 months in situ at L5-S1

from a 43-year-old female patient due to nerve root impingement. In general, the components exhibited highly polished surfaces, similar to those observed on explanted metal-on-metal hip implants. The primary wear mechanism was microabrasion, which was evident by microscopic scratching of the articulating surfaces. Focal microplasticity was also observed at the apex of the dome and the anterior/posterior vertices of the cupped component, suggesting that the primary motion in these locations was flexion/extension. Surface deposits, manifested as a smoky or hazy discoloration, were observed on both components, consistent with organic films previously observed in well-functioning metal-on-metal hip joints. The surface features of the Maverick retrieval were compared with wear-tested components in a study by Paré et al.[84] The surface topography of unidirectional tested components was found to be more severely abraded than the components that were tested under combined flexion-extension, lateral bending, and axial torsion. Although only a single retrieval was available for comparison at the time of the study, the retrieval results were more closely comparable to the wear test results with combined motion.

Dynamic motion preservation studies

Dynamic stabilization devices are nonfusion devices designed to stabilize the motion segment in lieu of fusion. Retrieval analysis for the Dynesys system has been reported. The system consists of fixed pedicle screws, polycarbonate urethane (PCU) spacers that resist extension and compressive loads, and poly(ethylene-terephthalate) (PET) cords that resist flexion and tensile loading. Trommsdorff et al. have examined the biostability of retrieved spacer and cord components.[18,85,86]

In a retrieval study of 12 cords retrieved from 10 different patients (implanted 2–5.5 years), changes in surface chemistry were evaluated using attenuated total reflectance Fourier transform infrared spectroscopy (ATR-FTIR).[85] Molecular weight distribution was evaluated using gel-permeation-chromatography (GPC). The retrieved cords were cleaned using an enzyme solution to remove biological residue. The authors reported that the ATR-FTIR spectra obtained at different positions along the retrieved cords showed no signs of significant hydrolysis. Molecular weight analysis conducted on 2 retrieved cords (3.3 and 5.5 years) did not show evidence of a significant change in molecular weight distribution. The authors concluded that the Dynesys PET cords demonstrated good biostability up to 5.5 years.

In a case study by Trommsdorff et al.,[86] a system that had been implanted for 5.5 years was retrieved from a L3-4 in a 56-year-old patient who had an abscess in proximity to the left spacer, which was presumably caused by infection. The contralateral component was not infected. Both spacers were retrieved and their chemical structure was compared to a control component using ATR-FTIR. SEM was also used to evaluate regions on the spacer surfaces. Compared to the control spacer, the left spacer that was adjacent to the abscess showed changes in the IR-peaks that could be attributed to hydrolysis of the soft and hard segments of the PCU. On the right spacer, there was no remarkable chemical degradation. No change in the chemical structure was observed in either spacer at a depth of 100 microns or in the bulk material. SEM demonstrated microcracks on the left spacer, while the right spacer was described as "perfectly smooth." The authors concluded that the functionality of the implant was not impaired because the degradation was limited to the surface layer (<2.5% of the wall thickness).

In a larger study of 50 retrieved Dynesys systems with implantation times ranging from a few months to up to 5.5 years, the investigators conducted optical microscopy, SEM, ATR-FTIR, and GPC analyses of the PCU spacers.[18] The PET cords were also inspected using optical microscopy. The PET cords demonstrated minor damage to the outermost layers in the regions of fixation, but were intact elsewhere. The PCU spacers typically demonstrated minor deformation due to cold flow of the material. Regions of wear were observed, which the authors concluded to have been from articulation of the spacer with the facet joint. No changes in molecular weight distribution were observed in 3.3- and 5.1-year retrievals. At the surfaces of the PCU spacers, small changes in chemistry were observed, which the authors attributed to the absorption of biofluids and minor hydrolytic changes of the material. At a depth of 100 microns below the surface, no change in the chemistry of the PCU was found. The authors concluded that the PET cords and PCU spacers were biostable over an implantation time of up to 5.5 years.

In a more recent abstract by Trommsdorff et al. summarizing the findings of 64 retrieved Dynesys systems, the results related to the PCU spacers were similar.[87] The systems were implanted for up to 7 years. The authors also report the incidence of screw loosening (20% of retrievals) and screw breakage (16% of retrievals). The screw breakages occurred at approximately 1/3 of the screw length from the tip of the screw and apparently due to fatigue fracture. The authors reported that this rate was in the same range or lower than that of other comparable designs.

Ianuzzi et al.[6,7,88] have reported similar results from their collection of retrieved Dynesys systems, which consisted of 44 spacers from 10 patients implanted 1.8 years (range, 0.7–4.2). The systems were primarily revised for persistent pain (9/10 patients) and screw loosening (7/10 patients), with one patient experiencing complications due to implant migration. Optical microscopy was conducted to evaluate spacer deformation and wear. ATR-FTIR was utilized to evaluate changes in surface chemistry compared to two control components. Similar to the results of Trommsdorff et al., the researchers observed a focal region of abrasive wear along the length of 27/44 spacers, which was likely due to impingement with surrounding bony structures. One spacer exhibited short surface cracks that extended from the center of the spacer to the outer surface. The authors also

observed changes in chemical structure on the surfaces of the spacers, although evidence of material degradation was observed in 2/44 spacers and only in regions where the spacer would be in contact with biological fluid. The findings were determined to be incidental, as the components from the short-term retrieval study were revised for reasons unrelated to wear, surface damage, or biostability.

The findings from 2 separate groups of researchers demonstrate that components from Dynesys systems may undergo deformation, wear, and changes to surface chemistry. These findings are from relatively short-term retrievals (up to 5.5 years). Thus, the long-term effects of these phenomena are unknown at this time and require further investigation as spinal implants composed of similar materials and/or design continue to be developed and utilized.

Recommendations for future testing and research

Based on the body of retrieval evidence for Charité discs, wear simulators of the lumbar spine should be tuned to produce a similar extent of cross-shear, as observed in hip replacements. This evidence suggests that the option for unidirectional wear testing currently offered in the recently approved ASTM Standards for wear testing of TDRs are not appropriate for the lumbar spine. In hip and knee simulator tests, 1 million cycles correspond to about 1 year in vivo; little is known about the number of duty cycles cervical disc replacements experience in vivo. However, recent comparisons between lumbar and cervical devices and simulator studies employing protocols detailed in ISO standards provide support for short-term intervals to be assessed when conducting a wear test. Based on simulator testing and retrieval analyses, we begin to see similar wear patterns (in the case of the Prestige cervical disc) as early as 100,000 to 200,000 cycles of wear testing using the ISO protocol. In the case of the Charité TDR, analysis of the penetration rates also suggests that 100,000 to 200,000 cycles correspond, on average, to 1 year in vivo. It may be that the similarity in design and material explains the consist results, thus validation testing with a greater number of designs and bearing materials is necessary. Current data support the hypothesis that wear mechanisms within the first million cycles of testing in a simulator may be clinically relevant, and thus provide important benchmarks for the validation of standard wear testing protocols for TDRs.

Because of the prevalence of impingement seen in the Charité retrievals, the authors recommend that impingement fatigue tests be developed to evaluate the performance of total disc replacements. In the Charité, impingement can occur during regular flexion or extension activities and has been shown with in vitro cadaveric tests.[89] Impingement can also occur due to subsidence, subluxation, or migration of the endplates. Because resistance to chronic impingement damage is desirable, fatigue test methods should be developed to reproduce the rim fracture modes observed in the Charité retrievals presented in this study. Once validated, the protocol could be used to screen implant materials for fatigue resistance under clinically relevant loading conditions. Additionally, given the potential for component oxidation, it would be useful to precondition test specimens using accelerated aging prior to rim fatigue tests.

The recommendations for standardized wear testing and periprosthetic tissue analysis in this paper are based on long-term wear findings of retrieved components of a single lumbar total disc design and short-term findings from other designs. These include evaluations in wear simulators, retrieval analysis of motion preserving spinal implants, and assessment of wear debris and biological response in periprosthetic tissue. It remains to be seen how generalized these findings are to other lumbar total disc replacement designs, particularly those with newer material couples, as well as to cervical spine designs.

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