LIGHT MICROSCOPIC AND SCANNING ELECTRON MICROSCOPIC RETRIEVAL ANALYSES OF IMPLANTED BIOMATERIALS RETRIEVED FROM HUMANS AND EXPERIMENTAL ANIMALS

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This paper reports analysis obtained from 200 implant cases retrieved from humans and submitted to the American Academy of Implant Dentistry Research Foundation, Medical College of Georgia implant retrieval center. The samples that were not decalcified were embedded in polymethylmethacrylate and examined with scanning electron microscopy and routine light, polarized, or Nomarski microscopy. Cases included both orthopedic and dental implants, as well as entire mandibles and portions of maxillae obtained at autopsy. A significant number of submitted implants had substantial amounts of adhered bone, which permitted evaluation of human bone remodeling to osseointegrated implants. These implants failed because of implant fracture. As was observed with animal studies, healthy bone supported these implants, with the bone containing an interdigitating canaliculi network that provided communication between interfacial osteocytes and osteocytes deeper within the remodeled osteonal and trabecular bone. Early dental implants containing a coating of beads showed a connective tissue interface, which corresponded to the bead surface of specific orthopedic implants that underwent some degree of micromovement. This is in contrast with the excellent response reported for successful contemporary beaded implants. Significant numbers of osseointegrated fractured hydroxyapatite (HA)-coated dental implants demonstrated the adequate serviceability of these implants before biomaterial fracture. In contrast, the HA coating was dissociated from retrieved orthopedic implants, leading to extensive cup loosening and case failure. This study, therefore, underscores the need for evaluation of failed human dental and orthopedic implants. Correlations can be drawn between human retrieval and experimental animal studies.

INTRODUCTION

Dental, oral, and orthopedic implants probably originated in ancient Egypt, developing from transplantation and implantation of animal and human teeth. Eventually, implanted biomaterials were introduced to provide esthetics after death because a full complement of body parts was important for burial. In fact, a metallic screw was discovered that acted as an ortho-
pedic fixation device for a dislocated femoral head. Other biomaterials were used for dental implants to ensure proper burial esthetics. Archaeology, therefore, provided us with the first implants for retrieval analyses. Implantology expanded through extensive in vivo transplantation and implantation of teeth into living patients until implantation with biomaterials such as bone, shells, and metals became more available. The pre-Columbian Mayan civilization made use of shells and bone for implants. Scanning electron microscopy was utilized to evaluate the occlusal surfaces of the implants, with the resultant observations verifying that the implants were, in fact, used for mastication.

The barber poles, with their red and white stripes, were reminders that the first surgeons were also barbers. In these cases, replantation and transplantation of teeth were the state of the art in these procedures as early as the 1500s. However, this transplantation of teeth resulted in numerous instances of disease transferal. These were what were considered the imperfections of natural tooth replacement at the time of the dawning of the 20th century. Peer-reviewed implantation protocols became apparent in the late 1890s, with Greenfield2 eventually describing dental implants as the "missing link in dentistry" in 1915, because of the imperfections of natural tooth replacements.

Two National Institutes of Health (NIH) consensus conferences3,4 have described the enormous growth in the field of oral implantology in the 1980s. The explosion of clinical and experimental research in the decade of the 1990s has documented the efficacy of oral and dental implantology protocols. Further, total joint arthroplasty has proven to provide outstanding service for the rehabilitation of a diverse patient population. Concurrent with the explosion of orthopedic and dental implantology, a plethora of implant methodologies and designs can readily be identified.

However, with this explosion of implant designs and the increased number of failed implants, an increase in the number of failed implants has been reported.5-11 This increase in the number of implants being removed from patients for various reasons underscores the fact that orthopedic and dental implants have become part of the normal treatment arsenal for rehabilitation of the patient who has lost function because of disease, neglect, or trauma. This increase in the amount of reported failures does not mean that implants are a poor treatment option. Rather, this increase in the number of failures only underscores the dramatic increase in implant use. In reality, current implant treatments are remarkably successful.12-16 This is in stark contrast to the rather poor serviceability rates reported17,18 for implants in the early decades of implant use.

Of particular interest is the increased use of coatings for orthopedic and dental implants. Beads have been sintered on metallic coatings since the early 1970s. Pilliar and coworkers were instrumental in the application of beads to orthopedic implants and subsequently dental implants. Excellent clinical and experimental results have been reported for press-fit beaded orthopedic implants and for beaded dental implants such as the Endopore implant. This current retrieval report evaluates beaded implants both from early experimental animal studies and current retrievals. Further, the application of thin coatings of hydroxyapatite (HA) have been extensively used in dental and medical fields. Even though there are promising reports of the advantages of coating implants with this biomaterial,16,19 there is an increasing number of reports11 that provide conflicting data and urge caution for the use of HA coatings on implants. Because of the apparent controversies of the benefits and risks of coating implants with HA, two featured international symposia have attempted to address these issues. In 1994, the International Association for Dental Research Symposium entitled “Hydroxyapatite Coatings on Dental Implants: Benefits and Risks” examined the effects of HA coatings on dental implants,20 and in 1997, the American Association for Osseointegration/International Congress of Oral Implantologists World Congress Symposium21 entitled “Surface and Coating Variability on Implanted Biomaterials” examined the effects of HA coatings on both dental and orthopedic implants. The benefits (enhanced initial fixation) versus the risks (HA delamination or dissociation) were addressed, with results disclosing increased enthusiasm for coatings on dental implants and less enthusiasm for orthopedic implants. Further examples of coatings, as addressed in this report, were coatings of porous alumina oxide. All three examples of coatings (beads, HA, and alumina oxide) demonstrate the desire to increase surface texture for bone growth.

It is now considered critical to examine failed dental and orthopedic implants to identify causal determinants for failure. Such analyses should include studies on the implant itself (i.e., biomaterial failure) and studies of tissue remaining adhered to the implant upon removal (biological analysis). Lemons5 suggests that the biomaterial and biomechanical properties directly influence tissue interface responses. This suggestion is supported by Brunski.22 Such biomaterial–oral tissue interactions need to be examined, both with experimental animal and human implant data. It should be noted that one of the conclusions of the 1988 NIH Implant Consensus Developmental Conference was that when failures occur, a failure analysis should be performed and reported.4

As a response to this mandate, an implant retrieval center was established at the Medical College of Georgia in association with the American Academy of Implant Dentistry Research Foundation. This Center has
been designated the AAIDRF-MCG Implant Retrieval Center and was established in 1990 as a service to the dental and medical professions in general and to implantologists in particular. More than 200 implants have been examined. The purpose of this paper is to present representative histopathological results of these implants sent to our laboratory for diagnostic review.

**Materials and Methods**

After removal by the clinician for various symptoms, all implants were immersed in 10% neutral buffered formalin and sent to our laboratories. On receipt, the samples were placed into fresh fixative for an additional 7 days. The technique for processing the implant specimens has been previously reported. Briefly, the samples were dehydrated in increasing concentrations of ethanol to absolute ethanol. The samples were transferred to acetone for 24 hours. Thereafter, the samples were placed into a 1:1 ratio of acetone to methylmethacrylate monomer for 24 hours, followed by immersion into 100% methylmethacrylate monomer for 24 hours. The samples were vacuum infiltrated in polymethylmethacrylate at room temperature for 7 to 21 days. Once hard to the touch, the samples were cured in a 37°C oven for 24 to 72 hours.

The plastic embedded blocks of tissues that were not decalcified attached to the retrieved implants were sectioned on a slow-speed saw (Buehler Ltd, Isomet 11-1180) affixed with a diamond wafering blade. For histologic examination, sections were cut at between 120 and 200 µm, with some sections subsequently ground to between 50 and 75 µm. The final sections were stained at 50°C via a basic fuchsin-to-ludine blue combination stain and examined with a Zeiss Axiophot photomicroscope with normal transmitted light, polarized light, or Nomarski differential interference contrast microscopy.

Alternatively, peri-acetabular and perifemoral tissues were obtained with the retrieved orthopedic implants at time of operative revision. These tissues were fixed in formalin, dehydrated, and embedded either in polymethylmethacrylate, as above, or in paraffin for sectioning. Paraffin sections were cut at 5 µm and stained with hematoxylin and eosin.

For scanning electron microscopy (SEM), thicker sections of between 200 and 500 µm were cut and left unstained. These sections were either coated with gold and viewed as is with a JEOL SEM or were subjected to our plasma etching procedure, as reported previously before SEM analyses. Orthopedic acetabular and tibial components were photographed, fixed in formalin, dehydrated, and viewed *en toto* within the chamber of the SEM. Energy dispersive X-ray analysis was performed to examine the surface composition of the implants.

**Results**

Results will be reported as they relate to the four categories of coatings that are the focus of this report. As described in each section, both human retrievals and data from experimental animals will be presented. Overall correlations will be examined in the discussion portion of this paper.

The cases will be presented in the following order. The first category presents representative cases related to beaded coatings on implants. These cases include experimental animal studies and corresponding beaded coatings on retrieved orthopedic total knee components. The second category includes representative cases of osseointegrated HA-coated implants that failed because of implant fracture. Bone morphology can be evaluated in these cases with data compared with experimental animal studies. The third category represents alumina oxide-coated implants in comparing such coatings with HA coatings. Finally, in the fourth category, uncoated implants are evaluated. The bone-implant interface will be evaluated, and an interesting orthopedic retrieval will examine the effects of bone support when bone is not necessarily the interface desired.

**Beaded coatings on dental and orthopedic implants**

Cylindrical dental implants have been coated with various biomaterials since the early 1970s. At that time, McKinney et al inserted cobalt-chromium-molybdenum (Co-Cr-Mo) implants coated with Co-Cr-Mo beads into the edentulous mandibles of adult mongrel dogs. As can be seen in Fig 1, the implants extended transmucosally and were thus subject to certain occlusal loads. Even though portions of the implants were interfacial by bone (Fig 2), many of the bead surfaces were supported by fibrous connective tissue (Fig 3). This corresponds to images of the tissues supporting a small percentage of orthopedic total knee components retrieved upon revision. Press-fit titanium tibial trays were coated with titanium beads to enhance initial biological fixation when cementation was not used. In most cases, screws were also used to provide initial fixation of such press-fit trays to the prepared tibia. However, in a small sample of these cases, screw fixation was not used because of operative planning. From this subset of cases, four trays were obtained because of pain or implant loosening. As can be seen in Fig 4, the beads were interfaced by fibrous connective tissue. The tissues are healthy, exhibiting little or no inflammatory cell infiltrate. Bone does appose some of the implant surface (Fig 5), but the bulk of the beaded surface is apposed by fibrous connective tissue (Fig 6). The effect of biomechanical load may influence this histologic finding, as will be discussed in the Discussion section.

**HA coatings on implanted biomaterials**

As described earlier in this article, there are benefits and risks of coating implanted biomaterials with thin layers of HA. The benefits of coating implants with HA can be seen in Fig 7.

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FIGURES 1–6. FIGURE 1. Radiograph of a cobalt-chrome-molybdenum implant coated with beads in the mandible of a dog. The implant was inserted to extend through the oral mucosa, thereby being exposed to occlusal loads. FIGURE 2. Photomicrograph showing some trabecular bone remodeling to an early beaded implant placed into dogs. The bone extends around the bead. Magnification = ×70. FIGURE 3. Low-magnification photomicrograph disclosing fibrous connective tissue apposing the entire circumference of a bead-coated implant placed into the dog mandible. Magnification = ×20. FIGURE 4. Photomicrograph demonstrating the fibrous connective tissue interface to a bead-coated tibial tray from a total knee arthroplasty. Health trabecular bone is noted but is separated from the beads of the implant by the fibrous tissue. Magnification = ×35. FIGURE 5. Photomicrograph showing a bone-implant interface in the region of the tibial stem from the same case as seen in Fig 4. Bone was disclosed only in the stem component of this implant, not interfacing the tibial tray. Magnification = ×35. FIGURE 6. Scanning electron micrograph showing that the fibrous connective tissue adhered to and ingrew into the beaded surface of the tibial tray of the total knee arthroplasty case. The unmineralized tissue was found dispersed throughout the retrieved tibial component. Magnification = ×30.
FIGURES 7–12. FIGURE 7. Photomicrograph demonstrating the intimate bone interface to the osseointegrated implant coated with 50 μm of hydroxyapatite. A forming osteon is apparent with a central canal of the Haversian bone observed between the implant threads. Magnification = ×70. FIGURE 8. Photomicrograph of a similar implant that was trephined from the patient’s mandible because of the osseointegration of the implant. The circumferential lamellae of the apposing bone is apparent. The HA coating remains intact. Magnification = ×70. FIGURE 9. Slightly higher magnification of an additional HA-coated implant trephined from a patient’s mandible. The hydroxyapatite coating is intact within the grooves of the implant, with mature bone interfacing this coating. Circumferential lamellae of the osteonal bone is observed distal to the implant, with aligned lamellar bone interfacing the coating. Magnification = ×100. FIGURE 10. Photomicrograph of the bone interface to a threaded region of another hydroxyapatite (HA)-coated implant trephined from the jaw. Canaliculi extend from the interfacial osteocytes to osteocytes within the bone. This interdigitating canaliculi network can provide communication between these cells encased within healthy bone. The 50 μm HA coating is clearly identified. Image taken with Nomarski differential interference contrast. Magnification = ×100. FIGURE 11. Photograph of dental implant in which the hydroxyapatite coating has dissociated from the more coronal aspects of the titanium implant substrate. Little tissue interfaced this implant, which was extremely mobile at time of removal. FIGURE 12. Photograph of the normal total hip replacement construct. The femoral head (ball) is locked by a taper to the femoral stem. The femoral head articulates with the ultra–high molecular weight polyethylene liner, which inserts into the metal acetabular cup. The bearing surface is therefore the polyethylene liner.
Here, the coating is intact and is opposed by healthy mandibular bone. This dental implant was retrieved from a patient after implant component fracture. The implant was osseointegrated, but the case failed because of component breakage. The remodeling bone consists of a newly formed osteon, with a central canal containing a blood vessel. Similar implants have also been evaluated and again disclose the excellent bone-implant interaction (Fig 8). Again, the implant was osseointegrated at the time of implant component removal. Closer examination of the bone (Fig 9) displays healthy and viable osteocytes within the bone interfacing the HA coating on the implant. Further, an interdigitating canaluli network of adjacent osteocytes can be observed closely situated to the implant coating (Fig 10). The advantage of the HA coatings is the excellent bone-coating interaction. Figure 11 discloses the disadvantage of HA coatings on implanted biomaterials. Here, the HA has dislodged from the dental implant. Little tissue remains upon the failed implant that was removed, because of obvious implant loosening in vivo. Even though this is a drastic case (observed primarily in early implant retrievals), the scenario still exists.

In total hip replacements, the femoral head inserts into a polyethylene insert within the acetabular cup (Fig 12). The ultra-high molecular weight polyethylene insert serves as the bearing surface in the total hip arthroplasty. In cases of retrieved HA-coated orthopedic acetabular cups, it was found that the cup became devoid of the HA in vivo. As seen in Fig 13, only minimal fragments of HA remained intact on the cup surface. This loss of HA coating led to the loss of bone fixation and the failure of the implant. Such was the case in 10 of 40 such components that were consecutively placed in a series of patients who underwent total hip arthroplasty.

**Porous coatings on endosteal implants**

As an attempt to increase the surface area and texturing of the intrabony component of the Kyocera single-crystal sapphire alpha alumina oxide implant, it was decided to sinter a coating of porous alumina oxide to the substrate of the single-crystal sapphire implant (Fig 14). In animal studies\(^{26}\) bone ingrowth was noted within the porosity of the implant (Fig 15), providing excellent bone stability and osseointegration (Fig 16) for many of the implants.\(^{25}\) However, at times the porous coating dissociated from the implant substrate (Fig 17), leading to fibrous encapsulation of the implant, mobility, and ultimate implant failure. This delamination of the coating was similar to the delamination of HA coatings that was witnessed in early failures.

**Uncoated implanted biomaterials**

We have had extensive experience with uncoated titanium implants, both in experimental animal studies\(^{8,32}\) and in clinical implantology. Uncoated implants have been shown to be extremely successful and reliable. In clinical implant retrievals, as well as in experimental animal studies, bone intimately apposes both uncoated titanium (Fig 18) and uncoated alpha alumina oxide single-crystal sapphire (Fig 19) dental implants. Figure 18 displays the forming osteons of the woven remodeling bone at the early healing stage interfacing the titanium implant, whereas well-formed osteons make up the mature bone supporting the single-crystal sapphire implant in Fig 19. It has been well documented\(^{16-32}\) that uncoated implants elicit intimate interfacial bone adaptation. This can even occur when bone adaptation is not the tissue desired. This is the case with internal fixation with intramedullary (IM) nails to enhance long-bone fracture healing. One such retrieval is seen in Fig 20, which shows an IM femoral nail upon retrieval. The surface of the nail demonstrated a film of unknown character at time of retrieval (Fig 21). Light microscopic examination showed the film to be a thin coating of bone adhered to the titanium implant (Fig 22). The internal aspect of the nail contained the normal appearance of bone fragments and fibrous connective tissue (Fig 23).

It should be noted that bone adhered to an IM nail inhibits the removal of the nail if removal is part of case management.

**DISCUSSION AND SUMMARY**

The analysis of implant samples obtained upon revision and retrieval offers extremely important insights into the success and failure of implanted biomaterials. In contrast to retrievals obtained in the past, implants that are forwarded to our laboratories today are often well integrated in bone. Such samples allow the investigator to critically evaluate the human bone supporting these implants and to compare the results with those of experimental animal studies for which we can control many of the variables affecting implant-tissue interactions. We are fortunate to have carried out comprehensive light and electron microscopic studies in animal studies of the identical implants that we obtain from patients at the time of revision.

In the case of HA-coated implants, we saw early cases of drastic dental implant failure caused by coating delamination or dissociation. These early cases were often initiated in the mid-to late 1980s.\(^{8,32}\) In these cases (as represented by the implant seen in Fig 11 and by earlier reports\(^{30}\)), the coating was detached from the implant substrate. This may have been caused by the early coating development or to the inadequacy of the implant substrate design. This was the case with the HA-coated orthopedic acetabular cups, as seen in Fig 13. As previously reported,\(^{35}\) 10 of 40 consecutive cases of HA-coated cups were retrieved because of cup loosening and migration. Three-dimensional SEM analysis disclosed the dissociation of the HA coating in vivo. This coating was of an earlier compositional characterization, and the smooth metal substrate was probably inadequate for coating bonding. Such a loss of coating has always been a concern for clinicians and was thoroughly
discussed at the two symposia previously mentioned.\textsuperscript{20,21} That is the risk of HA coatings, or of any biomaterial coating, on an implanted device. This was again seen with the porous alumina oxide coating that was sintered on the single-crystal sapphire implant body (as seen in Figs 14–17). Here again, we see the problems with implant design. We previously reported the problem with neck fracture of this design in experimental animal studies,\textsuperscript{25} and this extended into similar failure in human clinical cases. When the coating delaminated from the implant core, as seen in the animal case reported here, the implant became encapsulated with fibrous connective tissue in the classic failure scenario first reported by Meenaghan et al.\textsuperscript{34} Such coating loss led to implant loosening and cup migration in the orthopedic implants and to excessive implant mobility with the dental implants.

However, the benefits of HA coatings are also manifested in the implant retrievals. Our more recent HA-coated dental implant submissions are represented in Figs. 7–10 and also as previously reported.\textsuperscript{33} In these instances, the implant was osseointegrated, but the case failed because of biomechanical failure of a component of the implant. This gave us the opportunity to compare the bone implant morphology with both human bone and experimental animal studies. We used the identical implants (Nobel Biocare) in subsequent comprehensive animal studies. Similar bone morphology was seen in both research models and is reflected by the photomicrographs of Figs 7–10. As seen in Fig 10, an interdigitating canaliculi network provided an avenue for communication between interfacial osteocytes and osteocytes deeper within the bone. This was identical to the appearance of the communication network in experimental animal bone with identical implants.\textsuperscript{35} We are currently investigating the effect of biomechanical load on underlying cell signaling in the animal model. Therefore, correlative studies such as this retrieval investigation of identical implants lets us begin to bridge the gap between animal and human studies. With the correlational microscopic techniques (routine light, polarized light, and Nomarski illumination) possible with the same sections, the mechanism of bone remodeling can be better understood. As seen in this study, osteonal and trabecular bone remodeling can be described with human bone and correlated with kinetic and ultrastructural investigations possible with experimental animal studies.

Biomechanical load was an issue with the retrievals of beaded implants. The successful use of beaded surfaces as a porous substrate for biological fixation of implants was previously described by Cameron et al.,\textsuperscript{36} Cook,\textsuperscript{57} and others. Recently, Deporter et al.\textsuperscript{18} and Pilliar have reported excellent experimental and clinical results for the Endopore dental implant system, a system that has many of the biomechanical characteristics of the earlier beaded orthopedic devices developed by Pilliar. The Profix Total Knee system (Smith & Newphew Richards, Memphis, Tenn) is a total knee arthroplasty system with which we have had extensive experience. The tibial tray is coated with a beaded surface to enhance initial biological fixation. A small percentage of these implants has been retrieved by our laboratories, and all were inserted without screw fixation. In these cases, as seen in Figs 4 and 6, fibrous connective tissue interfacial the bulk of the tibial tray. Only aspects of the tibial stem were directly apposed by bone. This is in contrast to the excellent bony support clinically observed for screw-fixed, press-fit Profix tibial trays. We suggest that potential micromovement of the tibial trays may be responsible for the interpositioning of the 100-µm-thick layer of fibrous connective tissue between the tray and the tibial bone. Perhaps screw fixation could have diminished this micromovement in the other cases, allowing bone to remodel to the beaded surface of these implants. In a rat model, Skripitz and Aspenberg\textsuperscript{39} suggested that bone resorption and potential prosthetic loosening could be caused by such micromovement and subsequent fluid pressure. We have also hypothesized this mechanism in early animal studies\textsuperscript{37} dealing with threaded implant designs. Further, upon review of early animal studies carried out with beaded dental implants by McKinney et al.,\textsuperscript{27} a similar connective tissue membrane was observed in these implants that were immediately subjected to occlusal load. Therefore, it seems likely that immediate fixation of implanted biomaterials is mandated for continued implant success. Coatings on implants offer promise for this initial biological fixation, especially with dental implants. Because of the magnitudes and immediate loads for orthopedic implants, durable biological fixation may require additional mechanical fixation.

With the advent of biomaterial (HA, TPS, beads) and biological (growth factors, proteoglycans) coatings on implant biomaterials, the coating quality must be assessed, and the benefits and risks of biological and biomaterial coatings need to be evaluated. This was the basis of early symposia, and we hope that it will be addressed in future meetings, particularly at the American Academy of Implant Dentistry. Such a symposium is in the planning stages for the 2001 Annual Meeting. This is an area of research that is mandated for continued coating use.

With the enthusiasm for implant coatings, it is often forgotten that uncoated implants are extremely successful. We have previously reported that similar bone contact length percentage values were disclosed for HA-coated and noncoated titanium implants.\textsuperscript{30} This built on the comprehensive transmission electron microscopic and light microscopic evaluations of the bone interface to similar implants.\textsuperscript{30–32} To these uncoated implants, a densely mineralized collagen fiber matrix directly interfaced the uncoated implant surface. Osteocyte processes interacted with the implant surface, as these processes
FIGURES 13–18. **FIGURE 13.** Photograph of an orthopedic acetabular cup retrieved at time of revision. This cup was of the same design as the 10 cups obtained at revision. The conical macroporosity is apparent at the cup periphery. Only small regions of retained hydroxyapatite are apparent. **FIGURE 14.** Scanning electron micrograph showing the porous alumina oxide coating that was sintered upon the single-crystal alumina oxide implant substrate in the two-stage sapphire implant. The coating was applied to provide extended surface area for bone ingrowth. Magnification = ×20. **FIGURE 15.** Scanning electron micrograph (backscattered electron imaging) disclosing bone ingrowth into the porous alumina oxide coating for this successfully osseointegrated ceramic implant placed into an experimental animal. Magnification = ×100. **FIGURE 16.** Radiograph demonstrating the osseointegration of a two-stage alumina oxide ceramic implant placed into an experimental animal. The implant supported a fixed partial denture for 24 months. **FIGURE 17.** Scanning electron micrograph (backscattered electron image) demonstrating the delamination of the porous alumina oxide coating from the single-crystal sapphire implant substrate on the right side of the implant. The coating is intact on the left side of the implant. Fibrous connective tissue (shown in black with this image) encapsulates the implant and separates the implant from the mandibular bone. The connective tissue is also observed interposed between the delaminated coating and the implant substrate on the right side. Magnification = ×16. **FIGURE 18.** Photomicrograph demonstrating the close juxtapositioning of newly remodeled bone to the surface of an uncoated titanium implant that was placed into a dog mandible. Osteocytes are apparent in the viable woven bone opposing this implant, which was in situ for 5 months. Magnification = ×200.
FIGURES 19±23. FIGURE 19. Photomicrograph demonstrating the close juxtapositioning of remodelled osteonal bone to the surface of an uncoated single-crystal sapphire implant which was placed into a dog mandible. The concentric lamellae of the mature osteons are apparent, with abundant osteocytes within lacunae in the viable compact bone apposing this implant, which was in situ for 12 months. Magnification = ×200. FIGURE 20. Orientation photograph of a titanium femoral nail removed from a patient after it was in situ for 6 months. The implant was submitted to the AAIDRF-MCG implant retrieval center for analysis of interfacial evaluations. FIGURE 21. A slightly closer look at the femoral nail of Fig 20. A textured material is apparent on the surface of the nail. The submitting surgeon desired to analyze this zone because the nail was difficult to remove at revision surgery. FIGURE 22. Photomicrograph of the textured material zone noted in Fig 21. The film was demonstrated to be a thin layer of bone, which remodelled on the surface to the titanium nail. The bone was shown to be lamellar in nature and was intimately juxtaposed to the implant surface. Osteocytes were abundant in this cellular mineralized matrix. Magnification = ×35. FIGURE 23. Photomicrograph displaying the bone fragments and fibrous connective tissue within the internal aspects of the nail. This is what would be expected within this region. Magnification = ×35.
extended through a canaliculi network. This intimate bone-implant interface observed for uncoated titanium implants was also seen with the tibial nail reported on in this manuscript. Even though this was not particularly desired, the bone formed an adhesive layer on this implant within a relatively short period of time (6 months). Uncoated implants can be, and are, very successful implanted biomaterials.

Failure scenarios can occur because of various reasons. Obviously, surgical and prosthetic considerations are a concern. However, with the vastly improved surgical and prosthetic armamentaria currently available that were not available in the early periods of implantology, this concern appears to be less of a problem, because in-depth training is available. However, clinicians involved in oral implantology today have far more educational opportunities available and have a wealth of scientific data to draw upon. These data include observations on bone dynamics, bone vascularity, temperature thresholds for drilling, and extensive periodontal research. This seems to be reflected in the cases we are currently obtaining at the AADR-MCG retrieval center, where more and more case failure appears that is caused by biomaterial failure than failure attributed to surgery and prosthetic restoration. Periodontal problems still are attributed to some failure caused by poor patient hygiene, but even this seems to be diminishing.

This study, therefore, underscores the need for evaluation of failed or retrieved human dental and orthopedic implants. Generally, failure of implants placed longer than 10 years before may be caused by loss of bone support, connective tissue encapsulation, and inflammatory cell infiltrate (i.e., biological failure). Failure of more recently placed implants could also be caused by this scenario, but failure was more often ascribed to biomaterial failure.

ACKNOWLEDGMENTS

This study has been funded by the American Academy of Implant Dentistry Research Foundation. The authors are appreciative of the numerous clinicians submitting implant samples to the AADR-MCG retrieval center (Dr. David E. Stefflik, director). Portions of this paper have been, or will be, presented to the American Academy of Implant Dentistry, International Association for Dental Research, the Society for Biomaterials, and the Orthopaedic Research Society.

REFERENCES

21. Stefflik DE, Meenaghan MM. Surface and coating variability on im-