

The Technology of Hip Replacement

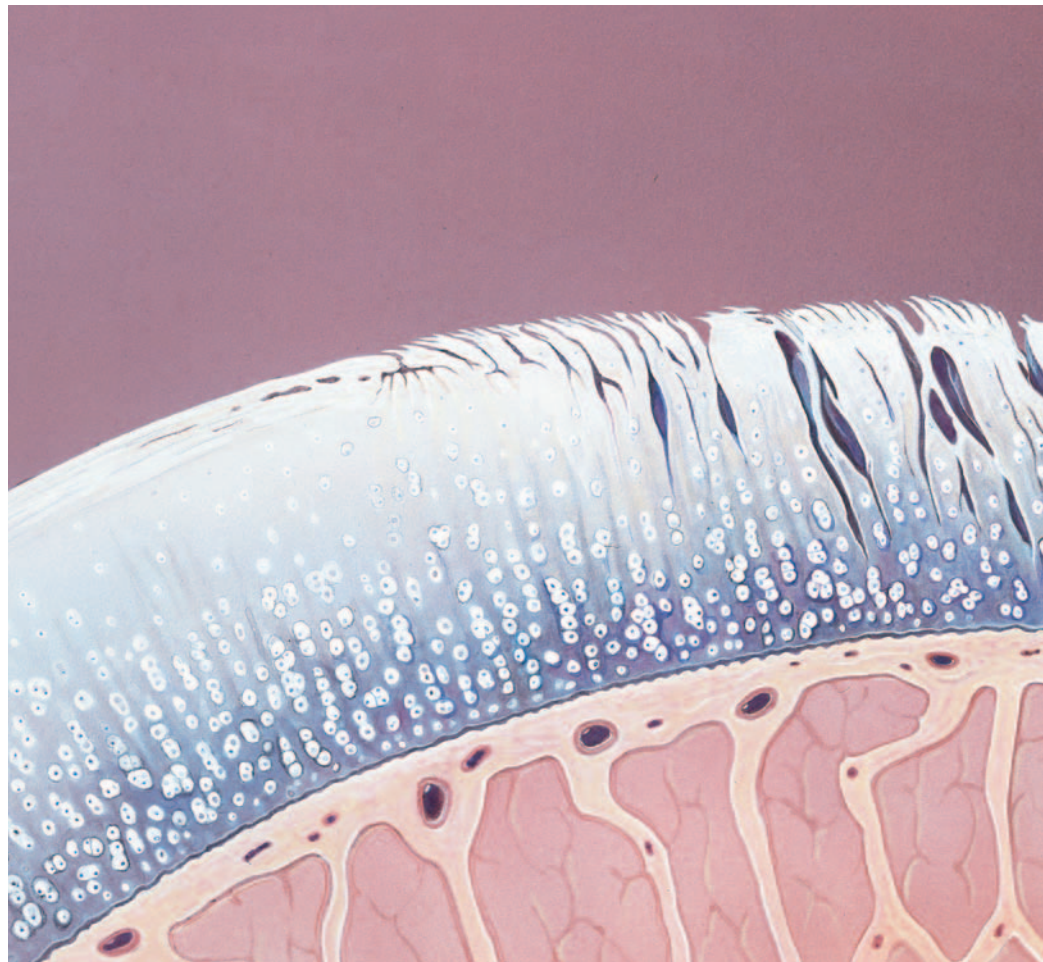
by Michael B. Mayor and John Collier

Between 80 and 90% of hips destroyed by rheumatoid arthritis can be restored to useful function and rendered free of pain by total hip arthroplasty. With more than 100 implant designs on the market and with surgeons performing hip arthroplasties according to idiosyncratic precepts arising out of their training and experience, useful comparisons of results are scanty. It is generally accepted that the main postoperative problem is long-term loosening of the prosthetic parts. Some solutions, such as cementless insertion and modular implants, have given rise in turn to other difficulties. Innovative efforts to improve hip implants offer hope to younger patients who could also benefit from total hip replacement.

Progressive damage to joints becomes increasingly prevalent as the population ages and can result from any of more than 50 different disorders. As the joint surface is degraded from whatever cause, the various forms of arthritis come to remarkably similar ends. Once the intimate architectural details that characterize normal articular cartilage

are destroyed, a rapid downhill course renders the joint's surface bald, polished, and painful. The result is that raw bone articulates against raw bone.

In the body's struggle to overcome the damage, nothing seems to work. A frustrated attempt to lessen rising levels of pressure produces the familiar marginal joint spurs, or osteophytes. Surface bone,



once subchondral, undergoes sclerosis. Fragments of joint surface cartilage are driven through the surface bone to form cysts within the underlying marrow, filled also with inspissated joint fluid. Loss of exquisitely lubricious chondral surfaces causes major increases in local friction, and the inevitable local heating that goes with it. Minute fragments of tissue are ground free from the surfaces and, when ingested by synovial lining cells, create the concomitant inflammatory reaction that gives arthritis its name.

With loss of congruency, and the development of marginal bone spurs, comes loss of mobility, both in limber range of motion and in endurance for distances walked. The inflamed joint is so sensitive that turning over in bed in sleep is enough to cause the victim to start awake, further eroding the quality of life available for the arthritis

sufferer. The arthritic joint pours out a stream of pain signals to the central nervous system, where reflex arcs inhibit the motor horn cells from recruiting the muscles they control to strong contraction. Profound atrophy in the involved musculature adds to the loss of function. As the involved joint loses ground, adaptive changes transfer stress to neighboring joints, placing them at risk of overload and damage.

Hip Arthroplasty Has a Long History

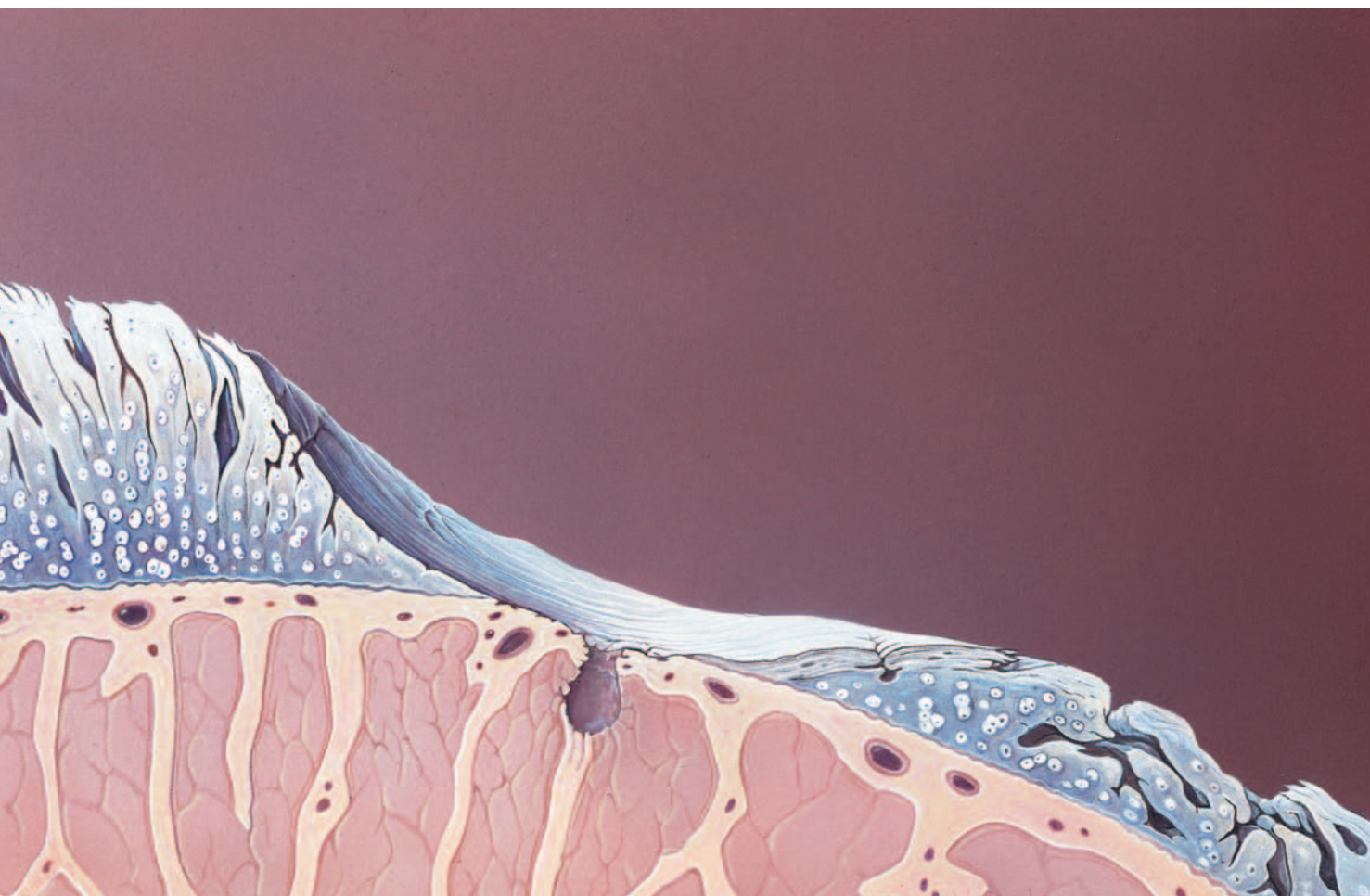
That an extract of willow bark was palliative for those with angry joints was understood in ancient times. Modification of the salicylates discovered in the bark extract produced a practical and inexpensive synthetic compound introduced into clinical medicine a century ago as aspirin. Anti-inflammatory agents have proliferated recently,

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Deterioration and inflammation of articular cartilage causes progressive joint destruction. Normal cartilage appears at the left and inflamed cartilage at the right in this illustration.



CAROL DONNER



COURTESY OF LADY CHARNLEY

Sir John Charnley

Does Bo Know?

Neither surgeons nor engineers will ever make an artificial hip joint which will last 30 years and at some time in this period enable the patient to play football.

—John Charnley, 1961

A traditional Charnley cemented arthroplasty with a 22-mm head and all-polyethylene cup.



yet despite the bulging pharmacopoeia, many joints grind steadily into profound disarray.

Surgical help for the joint that is beyond pharmacology is also of long standing. Interposition of thin layers of skin, or “cutis arthroplasty,” was first tried in France in 1885. John B. Murphy of Chicago later suggested the use of fascia lata, and pieces of chromatinized pig bladder were tried. So were longer-lasting materials, such as gold. Some patients were comfortable for a while, but most lost significant function, and many became severely uncomfortable with the passage of time.

In 1923 Marius Smith-Petersen at the Massachusetts General Hospital removed a piece of glass that had been accidentally implanted in a patient’s back about a year earlier. He found the fragment to be surrounded by a smooth membrane that contained fluid, and soon he was placing glass cups over arthritic femoral heads. The plan was to leave the implants until the desired membrane had formed, then to remove them; the problem was that many of them broke.

A corrosion-resistant cobalt-based alloy containing chromium and molybdenum was developed for use in turbine engine blades. Its first clinical application was in dentistry, and the surgical grade alloy was named Vitallium. In 1937, Smith-Petersen later said, his dentist suggested that Vitallium would be ideal in “mold arthroplasty.” It was; and the procedure matured as “cup arthroplasty,” in which the metal was left in place. Sadly, cartilage membrane failed to form in fully one in five hips so treated.

Most patients who came to surgery were managed by arthrodesis or osteotomy, accepting severe limitations of function in exchange for relief of pain. Austin T. Moore was the orthopedic surgeon for the Columbia State Hospital in South Carolina, and for his institutionalized patients mobility reduced the need for attendants and thus the cost of care. In a patient with a possibly malignant tumor, Moore re-

placed the upper end of the femur with a Vitallium prosthesis in 1940, reporting two years later that approximately 75% of normal hip function was gained.

Moore’s first prosthesis was fabricated under the direction of Harold Bohlman of Baltimore, who had already tried replacing femoral heads with Vitallium (“hemi-arthroplasty”). Stainless steel substitutes for both femoral and acetabular elements, precisely ground to fit and screwed or bolted in place, were being used as well in the late 1930’s. These approaches failed because the fasteners came loose or broke.

Jean and Robert Judet of Paris introduced a prosthetic femoral head made of a heat-cured acrylic resin, methyl polymethacrylate, in 1946. The Judet prosthesis fitted tightly into the acetabulum, and its short stem was driven down into the neck of the femur to make a stable joint. Because the stems of some of the early acrylic implants began to fracture, a steel core was added. Some enthusiasts of the Judet prosthesis thought nylon would last longer than acrylic. In fact neither held up well, and both were abandoned. Vitallium prostheses were reported to be working loose and in some cases penetrating the acetabulum.

The Charnley Total Hip Is the Standard

By the mid 1950’s more than 30 different types of hip arthroplasty had been introduced, none of which enjoyed any greater long-term success than Smith-Petersen’s. The modern era was ushered in by John Charnley at the Wrightington Hospital near Wigan in Lancashire, where the Manchester Regional Hospital Board had established a center for hip surgery at Charnley’s urging.

Over a 10-year period starting in 1948 Charnley had developed a hip stabilizing operation designed to obtain not more than 30 degrees of flexion, giving the sta-

bility of an arthrodesis while allowing patients to walk. He shaped the femoral head into a cylinder and made a hole in the acetabulum to accept it, thus shortening the lever arm of the body weight. By reattaching the greater trochanter to the outside of the femoral shaft, the procedure also lengthened the gluteal lever arm. These biomechanical alterations were retained in the new total hip arthroplasty.

Meanwhile the Judet acrylic prosthesis was being widely used. A squeak was heard for a time in some patients with this device, and Charnley understood what was happening. He wrote, "A squeak indicates that frictional resistance to sliding is so high that the surfaces are seizing together. Hence it seemed likely that the plastic of the original Judet prosthesis had adverse frictional properties when sliding against the bare bone encountered in the osteoarthritic acetabulum. It seemed possible, too, that the cessation of squeaking might be a sign not of improved lubrication but of loosening of the attachment of the prosthesis to the neck of the femur. In these circumstances the head of the prosthesis would be stationary in the acetabulum and all movement would be taking place between the femoral neck and the stem or spike by which it was originally attached to the bone."

On that account, replacing just the femoral head was rejected in favor of the Moore type of prosthesis with a longer stem that could be fixed in position with dental cement and would thus resist twisting. Also needed was a coefficient of friction approaching that of a normal joint, not to eliminate wear but to eliminate torsional stress. For his acetabular component Charnley chose polytetrafluoroethylene (Teflon) in 1957 because it was chemically inert and could be cut with a knife. The first Teflon sockets were thin; but engineering colleagues soon pointed out that a smaller ball and thicker socket would at once decrease the friction-

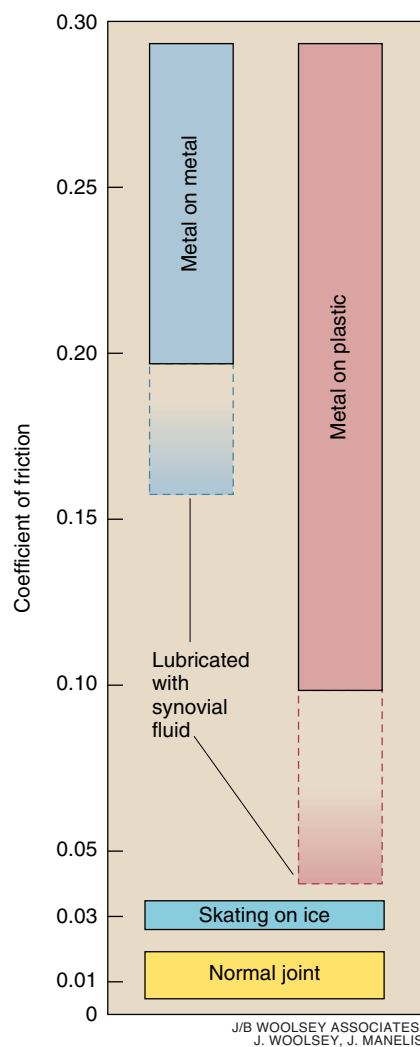
al moment between the two elements and increase that between the socket and the bone. Because abraded particles induced a granulomatous reaction, Teflon was superseded fairly early by ultra-high molecular weight polyethylene.

John Charnley's total hip arthroplasty was first used in its complete form in January 1960. By the end of that decade it had become the world's standard, and with modifications, so it remains. Few total hip procedures today include lateral relocation of the trochanter, but low frictional torque arthroplasty with cemented metal-on-plastic parts achieves relief of pain and improvement of function that were impossible before.

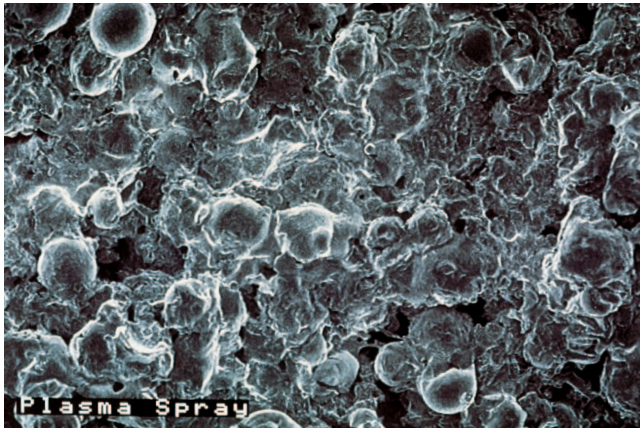
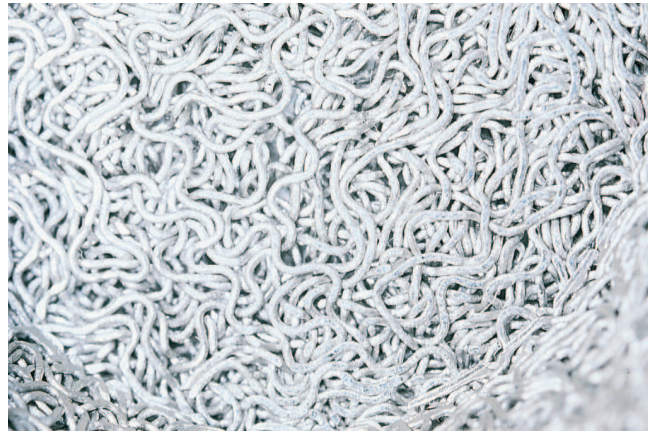
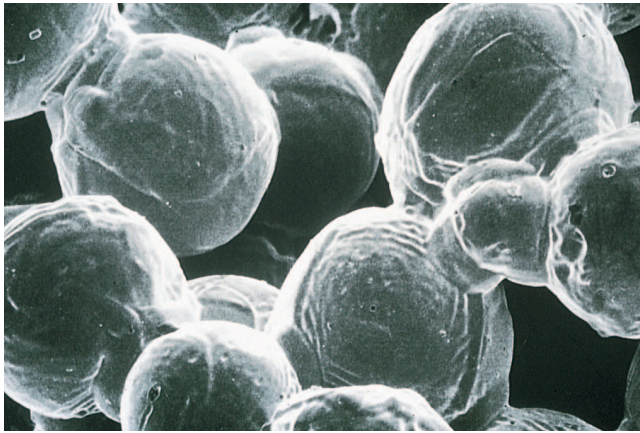
Technical Problems Limit Implant Longevity

At least 90% of total hip patients will be practically rid of pain, and about 80% will recover three quarters of their joint motion. Postoperative mortality of about 1.2% has more to do with the elderly patient population than with the surgical procedure or the implant, the chief culprits being thromboembolism, myocardial infarction, and congestive heart failure. The incidence of infections, which are acquired intraoperatively and which can be life-threatening, has been reduced to about 1% by using laminar-flow operating rooms and prophylactic antibiotics and by maintaining meticulous asepsis.

The major postoperative problem, and the one that may be the most amenable to a technological solution, is loosening of the prosthetic parts. Its consequences are progressive resorption of bone, formation of cysts, and a local histiocytic reaction that induces further bone destruction. Absorption of bone can also be caused by a granulomatous reaction to minute particles abrading from the plastic acetabular component, by disuse osteoporosis from decreased mechanical loading, and by fragmentation of the bone cement.



Coefficients of friction of normal joints compared with artificial joints and with an everyday low-friction experience. Neither engineering nor lubrication can approach the frictional coefficient of a healthy human joint.



PHOTOGRAPH BY TODD SMITH

Porous-coated implant surfaces encourage fixation by providing three-dimensional interdigitation. *Above, left*, Sintered beads on cobalt-chrome (original magnification X 40). *Above, right*, Diffusion bonded titanium wire mesh (X 10). *Left*, Plasma spray titanium coating (X 50).

The polymethylmethacrylate that surrounds a femoral implant (or a dental implant) has the same function as the mortar between bricks. It does not glue the parts together but absorbs the compressive force of gravity between them. Like mortar, bone cement has little resistance to shear, and the presence of laminations or air bubbles reduces its effectiveness. Under torsional or tensile stress it is liable to fracture. There are substantial torsional forces at work on the femur when a person rises from a sitting position, hence the effort to do without cement in hip replacement.

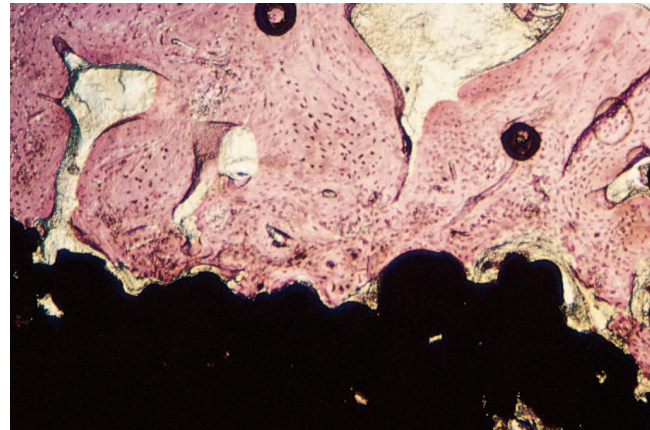
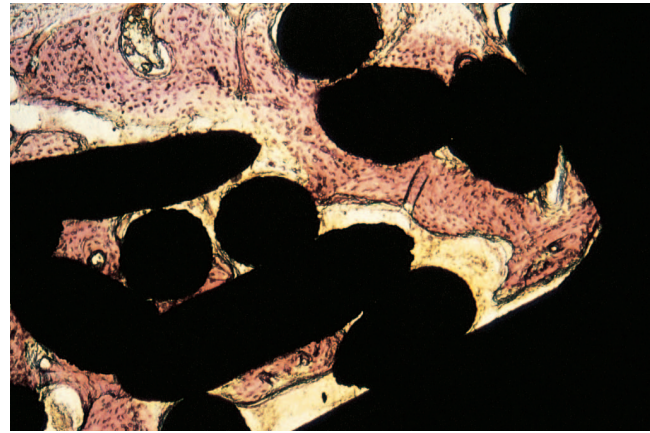
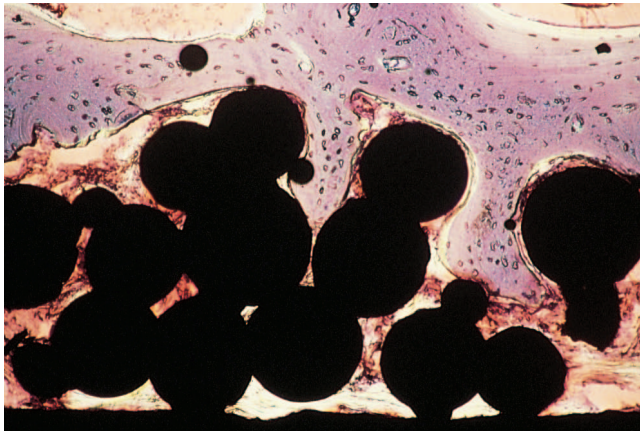
Most loosening results from technical problems centering on design and construction of the implants, insertion of the cement, and preparation of the femur. Loosening occurs in about 10% of patients, and the incidence might well be higher if the patients were younger. Improvements in surgical technique and in implant designs and materials can be expected to lead to longer implant life and reduced loosening rates as they are brought into general use.

Implant Materials Have Evolved

Stainless steel continued in use for some time after cobalt-chrome alloys were introduced because it is easier to machine and less expensive. Standard stainless steels are less resistant to corrosion than cobalt-based alloys, although more recently developed nitrogen-stabilized stainless steel has performed well.

To further improve the longevity of hip implants, Augusto Sarmiento and his colleagues at USC introduced titanium alloy in 1975. Titanium alloys are easier to work than cobalt-chrome but are more expensive. One attraction is their low modulus of elasticity: half that of cobalt-chrome, although still six times greater than cortical bone. High fatigue resistance is a key to extending the benefits of hip replacement to younger patients.

After 11 years of using both titanium and cobalt-chrome Sarmiento and colleagues published evidence that titanium gave a more uniform distribution of weight-bearing stress (less cortical neck resorption, less distal cortical hypertrophy). They also noted a more frequent occurrence of radiolucent lines at the bone-cement and cement-metal interfaces. These density changes, which Charnley also saw particularly between cement and bone with his early prosthesis design, were variously



Ingrowth of bone viewed by microscopy of stained sections. *Above, left*, In sintered bead coating (original magnification X 100). *Above, right*, In wire mesh titanium coating (X 25). *Right*, On plasma sprayed titanium coating (X 25).

thought to represent a fibrous tissue response to fragmenting cement, failure of cement to fill the medullary canal, osteoporosis, or osteolysis.

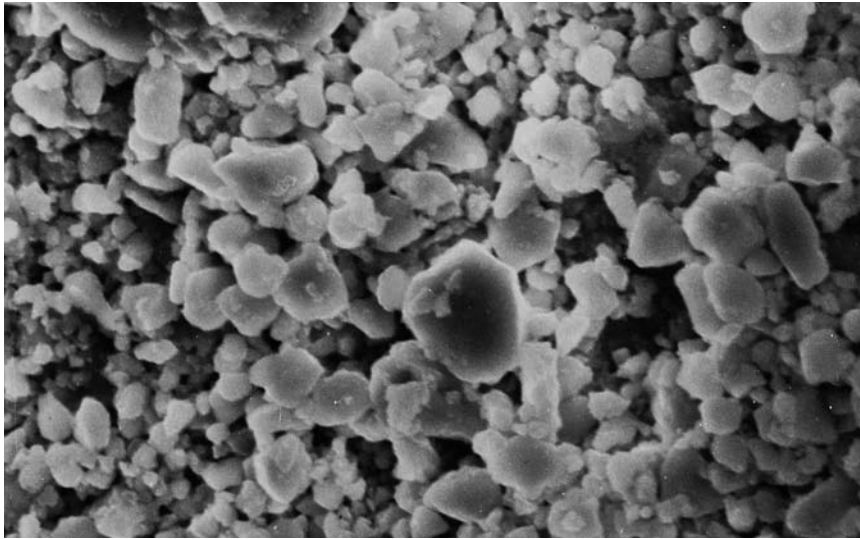
The possibility that the polymethylmethacrylate cement was failing and in one way or another producing both the radiolucent lines and the loosening of the prostheses had occurred to Charnley and to others. Robert Judet designed a prosthesis in which both elements were cobalt-chrome, cast with a porous surface to be press-fitted without cement. The first porous-coated prosthesis was placed in September 1971. Various beaded or grooved surfaces were subsequently tried, with varying degrees of success in inducing bone ingrowth.

Judet was aware that castings are inherently weaker than wrought metal pieces, and in any case the pores in the cast surfaces were too large for optimal bone ingrowth.

Manufacturers developed more effective porous-coated implants by sintering beads or particles of metal, by plasma spraying, and by attaching preformed wire or mesh.

Porous coating produces a greatly increased surface area to which fibrous tissue and growing bone can attach to transmit stresses to elastic bone instead of brittle cement. One disadvantage is that the manufacturing process reduces fatigue strength because relatively high temperatures are necessary to achieve metallurgical bonding. Another drawback is that porous-coated prostheses are difficult to remove if revision becomes necessary.

Other approaches to reducing the failure rate of cemented polyethylene acetabular components during the 1970's consisted of metal reinforcements. William H. Harris of Boston tried backing the plastic cup with a metal shell, but the long-term results were no better. M. E. Muller of Bern introduced an eccentric reinforcing ring



Hydroxyapatite applied by plasma spraying coats a metal prosthesis to a depth of 50 μm in this scanning electron micrograph (original magnification X 3000).

in the hope of distributing stress, but later analysis showed that the ring had no beneficial effect. Addition of a flange to the plastic acetabular cup is another attempt to distribute stress.

It became clear that loosening of the acetabular component was at least as severe and as frequent a problem as loosening of the femoral element. Moreover, revision of cemented acetabular components resulted in higher rates of loosening after shorter periods, probably because of continuing erosive damage to acetabular bone.

In 1974 James E. Bateman of Toronto and Richard P. Giliberty of the Nassau Hospital in Mineola, N.Y. independently published descriptions of novel designs of total hip prostheses primarily for fractures of the femoral neck. There were three parts: stem, cup, and liner. The femoral head articulated in the plastic liner, and the metal cup could move in the bony acetabulum, which it did during extreme ranges of hip motion. A hip prosthesis with two rotational axes is called a bipolar prosthesis, and both the Bateman and Giliberty designs were endoprostheses, assembled into a unit in the operating room. Neither was used for many rheumatoid patients, being intended for those with sturdier bones.

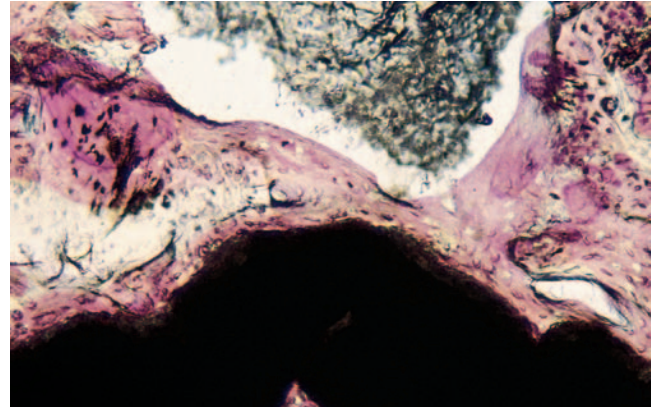
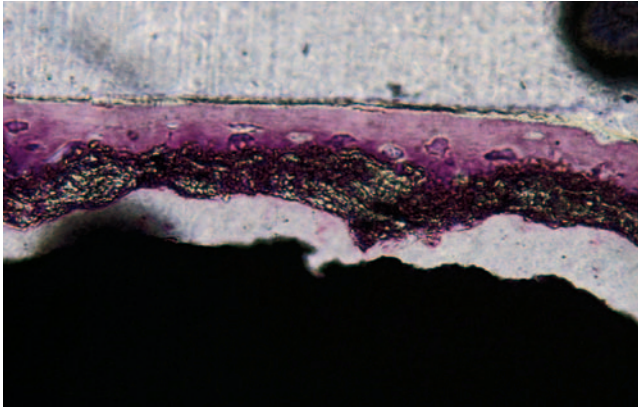
The fact that cementless hip replacements are also subject to bone resorption implicates polyethylene debris generated by the wear of the metal head against the polyethylene cup and provides a rationale for ceramic prostheses. In an attempt to improve on the low-friction characteristics of the Charnley hip, Pierre Boutin developed aluminum oxide components, borrowing once again from dentistry, and implanted the first ceramic hip in 1970. The theoretical advantages over the metal-on-plastic devices were superior hardness and smoothness.

Actual results were unsatisfactory until it was realized that the fit between the ceramic articular surfaces had to be extremely precise, the acceptable clearance being

just 15 to 40 μm . Assembled correctly, an alumina-on-alumina implant essentially does not wear at all. Its production of debris has been said to be 0.025% that of metal-on-polyethylene. Unfortunately, even the slightest impingement of the ceramic components generates debris that quickly damages the precise surfaces, resulting in catastrophic wear.

A promising alternative is a ceramic femoral head against a polyethylene acetabular component. Aluminum oxide femoral heads have been marketed in the United States since 1985, and zirconium oxide heads are also now available. These ceramics are harder than the usual metals and can be polished to a finer finish, which may result in less polyethylene wear. In part their introduction was a response to the discovery that metal heads are susceptible to damage by cement particles. Another answer to metal wear is bombardment of the implants with ionized nitrogen, which also enhances resistance to corrosion.

Concerns about the adequacy of bone growth into porous coatings, the strength of those coatings and the coated implants, and the possibility of ion toxicity led to investigations of synthetic hydroxyapatite as a coating material. Solid, sintered calcium-phosphate ceramics have been used as prosthetic



Bone grows tightly onto hydroxyapatite coating applied to a textured surface (*left*; original magnification X 100) and to a porous surface (*right*; X 75). The early use of thick coatings (*left*) could lead to coating separation. Thin coatings now used are more adherent.

bone for some time but are too brittle for use alone in hip implants. Applied in thin layers to titanium implants by plasma spraying, hydroxyapatite may increase osseous attachment over the short term, although all these coatings will resorb over time.

Modular components came onto the market in many varieties during the 1980's as suppliers sought to offer increased versatility. Attempting to provide, for example, the flexibility of a titanium stem and the durability of a cobalt-chrome head introduced new difficulties including fretting and corrosion. Corrosion in the crevice where the two metals meet takes four or five years to become evident and can lead to progressive weakening of the neck. Imperfect matching of the parts can produce wear debris. Modular acetabular elements, in which a plastic liner is placed within a metal shell, are subject to micromotion and the generation of debris as soon as they are implanted because of variations in dimensional tolerances and material properties.

Osseointegration with porous-coated metal is disturbed by micromotion. Rigid fixation of acetabular prostheses has been achieved by attachment to the ilium with screws, pegs, or spikes. Although screws provide the most satisfactory early results, metal fragments

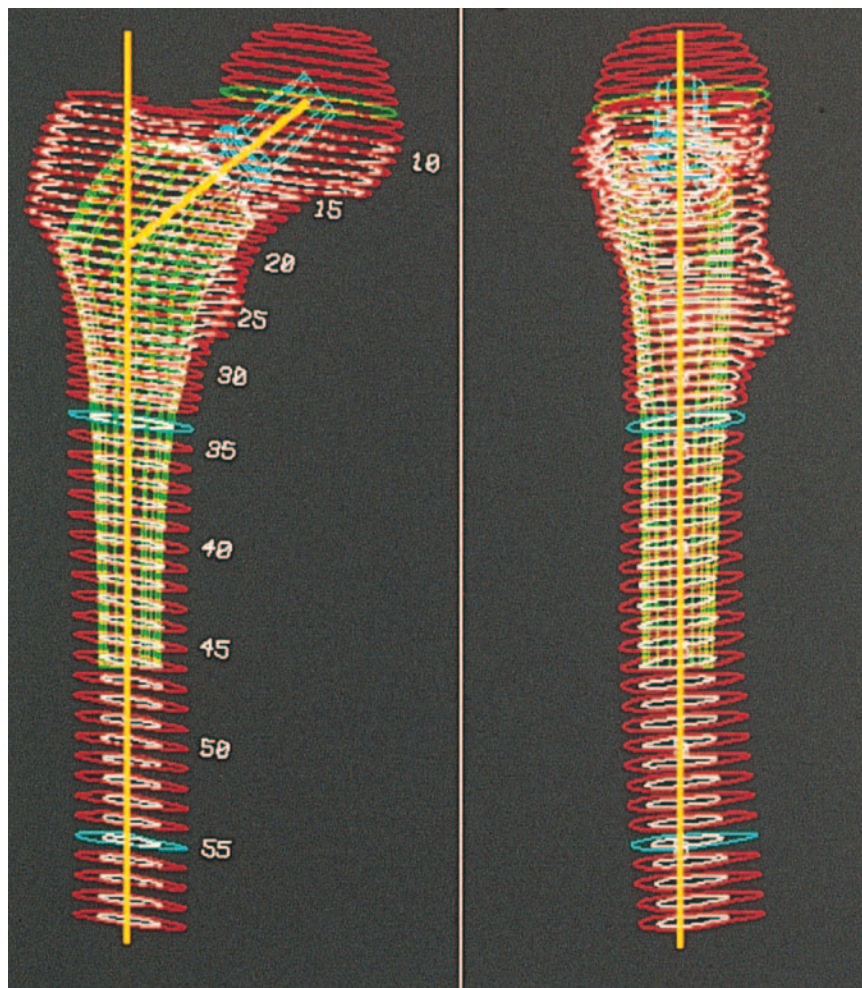
are generated as the screws work against the shell, and as micromotion increases there is erosion of the plastic liner as well. The generated particles migrate through the screw holes to bone, fostering osteolysis.

Modifications in the Use of Cement Reduce the Rate of Failure

Even if plastic and metal fragments are the chief instigators of bone resorption and loosening of prostheses, polymethylmethacrylate breaks up over time and contributes to long-term failures. Harris and associates at MGH pioneered the pressurized application of cement in the early 1970's and reported less than a 2% incidence of radiographic evidence of stem loosening at five years vs. 20% or more previously recorded.

An improved bond between cement and metal can be achieved by applying a thin PMMA coating to the metal surface of a prosthesis under high temperature and pressure during manufacturing, strengthening the cement-metal interface. The shear strength of the cement is low to begin with and lower at the interface, where it is believed that most fatigue fractures of the cement begin, so that any improvement is helpful. Some surgeons believe that a smooth-surfaced component and low bond

Computer-generated design of a femoral implant appears within the image of a femur built up from CT scans. Finite element stress analysis is incorporated into the design of the prosthesis.



COURTESY OF JEFFREY D. REUBEN, M.D.

strength between prosthesis and cement are desirable to permit the component to subside slightly over time and thus improve the fit.

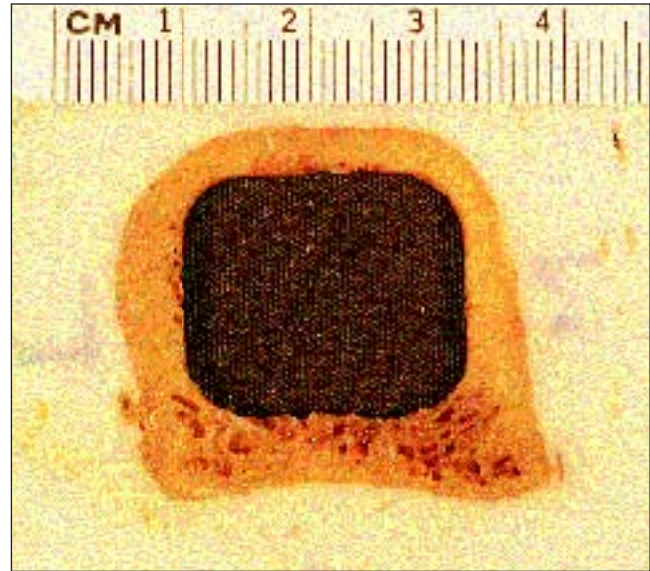
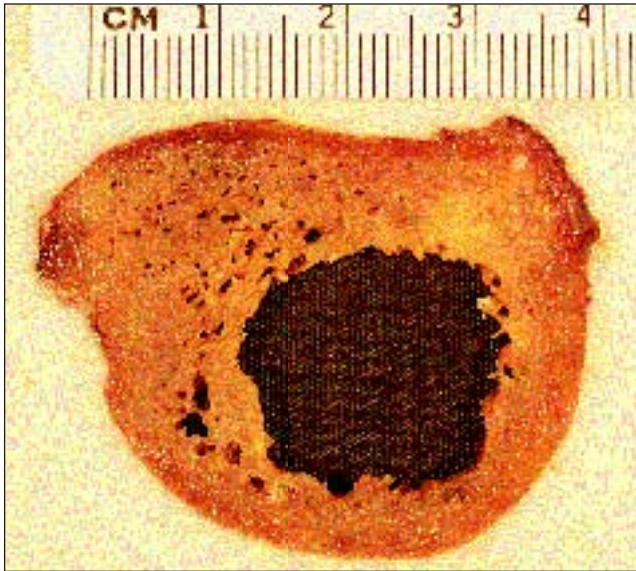
Computers and Robots Are Coming into Use

Computer-assisted design and manufacturing techniques have been used by the makers of prostheses for more than a decade, and some suppliers will produce custom shapes and sizes for special cases. But CAD-CAM systems are too complex for routine use at reasonable cost. Jeffrey Reuben of the University of Texas Medical School in Houston developed an expert system based on high-resolution CT scans and finite element stress analysis to design a prosthesis that fills the medullary canal as completely as possible. A femoral prosthesis that fills the canal

is theoretically less likely to subside or twist, and it may reduce stress shielding. Other recent prostheses also offer canal fill as a major design feature.

As for any cementless implant, the best candidates are younger people with better bone quality than the typical total hip recipient. There is a paradoxical aspect to that observation: the systems with the shortest track records are expected to go the longest distances.

Matching prosthesis to femur would also be more effective if preparation of the bone were more precise. Hand-held reamers and mallet-driven broaches, tearing instead of cutting the trabeculae, inevitably form an irregular cavity with limited contact between prosthesis and bone. Integrated Surgical Systems, Inc. of Sacramento adapted an industrial robot to prepare a medullary canal that



COURTESY OF INTEGRATED SURGICAL SYSTEMS, INC.

Robot preparation of the medullary cavity of a canine femur is an order of magnitude more precise than surgeons achieve with hand-held tools.

matches the dimensions of the intended prosthesis within 0.4 mm (which is ten times better than a surgeon can do) and that is correctly oriented to position the implant with respect to femoral rotation and version. Bench and animal experiments were successful; a human trial has yet to be reported.

Recent investigations at several institutions have focused on the cellular and subcellular mechanisms of bone resorption. Macrophages phagocytize metal particles and the smallest polymer fragments, releasing tumor necrosis factor and other mediators that initiate resorption at the bone-cement interface. Fibroblasts in vitro respond to low concentrations of particles of titanium, titanium-aluminum alloy, and chromium by

proliferating. Thus, metal debris may cause a fibrous membrane to form around prostheses. Such a membrane could give polyethylene debris access to the space between the implant and the bone. These studies and others employing molecular techniques will provide more precise understanding of why some hip implants fail.

Total hip replacement is successful for hundreds of thousands of patients each year. Failure rates are low, and relief of pain and improvement of mobility are great. Ongoing efforts to improve designs, materials, instruments, and techniques are aimed at longer implant life and a reduced incidence of osteolysis. These are the limiting factors, frustrating patients and their surgeons striving for untrammelled satisfaction.

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