Cementless Fixation in Primary Total Knee Arthroplasty: Historical Perspective to Contemporary Application

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ABSTRACT

Cemented total knee arthroplasty (TKA) has been considered the benchmark, with excellent clinical outcomes and low rates of aseptic loosening at the long-term follow-up. However, alterations of the bone/cement interface leading to aseptic loosening, particularly in younger and obese patients, along with increased life expectancy have led to a renewed interest in noncemented TKA fixation. Certain early noncemented designs exhibited higher rates of subsidence and component failure. Improvements in designs, materials, and surgical technique offer promise for improved results with contemporary noncemented TKA applications. In an increasing cost-conscious healthcare environment, implant cost is important to consider because press-fit prostheses are generally more expensive. However, this cost may be offset by shorter surgical times, cement costs, and the potential for osseous integration. Technological advances have improved the manufacturing of porous metals, with reported excellent midterm survivorship. Future prospective, randomized trials, and registry data are needed to delineate differences between cemented and noncemented fixation, survivorship, and patient-reported outcomes, especially in young, functionally active, and/or obese populations.
Lessons Learned From Early Designs

Femoral and tibial component fixation in early designs were inconsistent and had problems with initial rigid fixation. Radiostereometric analysis has shown that immediate rigid implant stability is essential for long-term biologic fixation in noncemented TKA. Early noncemented designs, including patch porous coating, did not achieve initial press-fit fixation to accommodate bony ingrowth because of implant liftoff, subsidence, and progressive loosening. Patch porous coating on femoral and tibial components created areas that allowed debris to reach the femoral and tibial metaphysis, causing notable osteolysis and loosening. Designs that provided complete or full undersurface coating mitigated this problem, especially on the tibial side.

Femoral fixation success was related with intrinsic mechanical stability of the geometrical press-fit obtained with multiplanar bone resurfacing. Although implant instability was uncommon with noncemented femoral implants, early generation designs demonstrated catastrophic failures from fatigue fracture from thin regions most notably along the anterior flange and posterior condyles (Figure 1). In addition, older generation femoral and tibial components created areas that allowed debris to reach the femoral and tibial metaphysis, causing notable osteolysis and loosening. Designs that provided complete or full undersurface coating mitigated this problem, especially on the tibial side.

Femoral fixation success was related with intrinsic mechanical stability of the geometrical press-fit obtained with multiplanar bone resurfacing. Although implant instability was uncommon with noncemented femoral implants, early generation designs demonstrated catastrophic failures from fatigue fracture from thin regions most notably along the anterior flange and posterior condyles. Designs that provided complete or full undersurface coating mitigated this problem, especially on the tibial side.

Early Noncemented TKA Designs

Boyd and Campbell developed the first vitallium, a cobalt-chromium (CoCr) alloy, interposition mold arthroplasty in 1940. In 1952, McKeever reported on a vitallium tibial implant with a truncated, T-shaped keel that was press-fit into slots in the tibial plateau. In 1953, a metal tibial articular plate hemiarthroplasty fixed with screws was introduced. Although some implant design improvement was observed during that time, most older designs had a high percentage of suboptimal results and catastrophic failures.

The first cementless-hinge acrylic TKAs were introduced and popularized by Walldius in the 1950s. By the late 1950s, the stemmed implant material was modified to stainless steel and later CoCr. Although several modifications were developed from the Walldius hinge design, many of these earlier implants had a high incidence of loosening because of the notable forces across the bone-implant interface. The first noncemented condylar TKA, the Kodama-Yamamoto Mark I knee, was initially reported in 1977. The first-generation noncemented TKA were developed from different vendors from the late 1970s through the 1980s.
The Imperial College London Hospital (ICLH) knee’s modification to the Freeman-Samuelson knee (FS) was an early noncemented condylar design that used a finned polyethylene peg design for patellar and tibial fixation. The tibial component was later modified to a metal-backed stemmed implant without a porous ingrowth surface. The CoCr femoral implant similarly did not have an ingrowth surface but used two polyethylene fixation pegs. Midterm results were marred with loosening, implant subsidence, and wear attributed to the polyethylene-bone interface and lack of a porous ingrowth surface.2

Similar to the ICLH-FS Knee, the Tricon-M Knee (Smith and Nephew), developed in the early 1980s, used finned polyethylene pegs for primary fixation. The femoral, tibial, and patella components had a beaded ingrowth surface for secondary fixation.2 The noncemented Press-Fit Condylar (PFC) (DePuy) knee system, with a Ti tibial baseplate with a smooth central stem and a metal porous undersurface, showed high survivorship in the short-term follow-up.12 The early Natural Knee I (NK-I) (Zimmer Biomet) system, introduced in 1985, had a Ti metal-backed patella, along with tibia and femoral components with a cancellous structured commercially pure titanium (CPTi) coating to ensure optimal material porosity and high-contact roughened surface area for bony osseointegration.2 The Ti was fixed with four peripheral spikes and two screws. By the early 1990s, the CPTi coating was further developed to adhere to a CoCr substrate, which was introduced in the NK-II system in 1995, along with an ultra-congruent polyethylene option for improved stability.2 The NK-I and NK-II were some of the more successful first-generation noncemented TKA designs. A comprehensive list of the first generation noncemented TKA designs are outlined in Table 1.

Second-Generation Modern Noncemented TKA Designs

Implant biomaterials and manufacturing innovation, along with design improvement, has led to renewed interest in noncemented TKA. Newer tibial designs include more robust pegs and keels that help with initial stability with porous coating under the baseplate only for long-term biologic fixation.13 Modern femoral and tibial peg designs are devoid of porous metals to mitigate stress shielding and bony resorption seen with older systems.14

Figure 1

A. Radiograph showing a crack originating from the inner beaded surface at the junction between the posterior bevel and distal surface of the nonfractured lateral side in a femoral condyle. B. Scanning electron micrograph of the inner beaded surface. The fracture joint remnants of several bead craters can be seen. (Adapted with permission from Whiteside LA, Fosco DR, Brooks JG: Fracture of the femoral component in noncemented cementless total knee arthroplasty. Clin Orthop Relat Res 1993;71-7.) Adaptations are themselves works protected by copyright. So, to publish this adaptation, authorization must be obtained both from the owner of the copyright in the original work and from the owner of copyright in the translation or adaptation.
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<th>Knee System</th>
<th>Manufacturer</th>
<th>Year</th>
<th>Off Market</th>
<th>Follow-up (y)</th>
<th>Survivorship (%)</th>
<th>Design Characteristics</th>
<th>Failure Mechanisms</th>
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</table>
| Kodama-Yamamoto     | Mizuho            | 1970 | 1974       | 15            | 86.6             | • Femoral undersurface—vitallium alloy  
• Tibia—flat and all polyethylene noncemented design  
• Fixation depended on fins on the femoral components and staples for the tibia | • Flat tibia and femoral geometry prevented effective range of motion  
• No initial stability caused early catastrophic failure |
| LCS                 | DePuy Warsaw, IN  | 1978 | 2001       | 17            | 97.9             | • Initially designed to address problems of fixed-bearing designs, notably the problem of wear because of high contact stress on the polyethylene common in the design of the 1970s  
• Decoupling of rotational forces of the femoral implant on the tibial polyethylene by allowing polyethylene rotational freedom on a polished CoCr tibial tray | • The hydroxyapatite coating (Duofix) of the LCS femoral implant led to early failures and FDA recall (2009).  
• A combination of retained alumina grit and a reduction in mechanical strength resulted in increased particle debris, metallosis, and early revision  
• Overall LCS Complete Knee System has maintained its overall design principles since introduction in the 1970s |
| PCA                 | Howmedica         | 1980 | 1996       | 6             | 77               | • First sintered porous-coated (CoCr) noncemented knee implant  
• PCL preserving design that was heat-pressed with metal backing of all three components  
• Pegs were coated with porous beads  
• Tibial baseplate did not have a stem/keel | • Primarily failed from polyethylene wear, inconsistent bone in-growth, and increased polyethylene wear of the patella  
• Flat articulation surfaces and heat-pressed polyethylene of the tibia promoted severe wear  
• Stemless tibia with CoCr porous coating did not provide adequate initial implant stability which led to high rates of implant loosening, subsidence, and collapse of the anteromedial tibia |
| AMK                 | DePuy             | 1980 | 2006       | 20            | 96.8             | • Femur composed of CoCr  
• Fixation of press-fit Ti tibial component obtained with 6.5 Ti screws through the baseplate into the tibial metaphysis | • Multiple reports of early radiolucencies around tibial screws  
• Notable tibial osteolysis from screw tracts |
| Ortholoc I          | Wright Medical Technology | 1982 | 1987       | 10            | 94.1             | • Patch porous coating with smooth metal ridges on the femur and tibia  
• Smooth anterior and posterior condylar flanges to avoid transmitting axial forces to those bony regions | • Femoral implant fractures and stress shielding from thin metal, sharp angles, and porous-coated lugs  
• Patella fractures included peg shearing, polymetal disassociation, and polyethylene wear |
| Tricon-M            | Smith & Nephew    | 1983 | 1988       | 10            | 90               | • Finned polyethylene pegs for primary fixation  
• Metal-backed tibia and patella components  
• Femur, tibia, and patella undersurface with porous bead ingrowth | • Poor initial stability led to early tibia subsidence and failures  
• Patella polyethylene increased delamination from poor patellofemoral mechanics |
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<tr>
<td>MG-I</td>
<td>Zimmer Biomet</td>
<td>1984</td>
<td>1991</td>
<td>11</td>
<td>74.4</td>
<td>Ti alloy for femoral, tibial, and patellar components</td>
<td>Suboptimal patella component design led to high incidence of patellar failures</td>
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<td>Ti fiber mesh undersurface for bone ingrowth</td>
<td>Patella failure was higher than tibial component failure which was higher than femoral failure</td>
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<td>The tibial baseplate did not have a stem/keel</td>
<td>Peg patella design placed notable stress on the implant-bone junction</td>
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<td>Initial implant stability caused high early failures</td>
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<td>AGC</td>
<td>Biomet</td>
<td>1984</td>
<td>—</td>
<td>10</td>
<td>97.1</td>
<td>CoCr tibial component with a central smooth stem/keel press fit without screws</td>
<td>Early tibial failures from subsidence likely from inadequate initial implant stability</td>
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<td>Undersurface of femur and tibia porous coated</td>
<td>Late patella failure from polyethylene wear from poor patellofemoral articulation kinematics</td>
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<td>PFC</td>
<td>DePuy</td>
<td>1985</td>
<td>1996</td>
<td>10</td>
<td>95.6</td>
<td>Ti tibial baseplate with a smooth central finned stem/keel with a porous undersurface</td>
<td>High failure rates of metal backed patella components from poor femoral trochlea design</td>
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<td>High rates of femoral and tibial aseptic loosening and periarticular osteolysis from polyethylene wear</td>
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<td>Natural Knee I</td>
<td>Zimmer Biomet</td>
<td>1985</td>
<td>1995</td>
<td>10</td>
<td>95.1</td>
<td>Ti femoral implant</td>
<td>Improved design compared with older noncemented TKA systems improved this implant’s survivorship</td>
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<td></td>
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<td>Ti metal-backed patella and tibial components</td>
<td>The Natural Knee had a deep trochlear groove for improved patellofemoral kinematics, asymmetric tibial baseplate, and cancellous structure Ti coating</td>
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<td></td>
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<td>Tibia was fixed with four peripheral spikes and two screws</td>
<td>Patella failure from edge wear</td>
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<td>The bone interface surfaces were coated with porous titanium</td>
<td>Polyethylene debris migration into metaphysis from screw tracts causing notable osteolysis</td>
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<tr>
<td>Genesis I</td>
<td>Smith &amp; Nephew</td>
<td>1988</td>
<td>1996</td>
<td>15.5</td>
<td>90.1</td>
<td>CoCr femoral implant and Ti tibial component</td>
<td>Radiographs showed a notable incidence of radiolucent lines around the smooth tibial stem</td>
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<td>Metal-backed patellar component that had improved designed compared with older noncemented systems</td>
<td>Survivorship similar to cemented Genesis I</td>
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<td>No endoskeleton of metal with thin polyethylene of the patella</td>
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<td>Profix</td>
<td>Smith &amp; Nephew</td>
<td>1993</td>
<td>2005</td>
<td>10</td>
<td>97.1</td>
<td>Ti tibial baseplate had a central corundum blasted stem with peripheral spikes and four screws for fixation</td>
<td>Long term Profix noncemented results similar to cemented designs</td>
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<td>Polyethylene debris migration into metaphysis from screw tracts causing osteolysis and aseptic loosening</td>
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AGC = anatomic graduated component; AMK = anatomic modular knee; LCS = low contact stress; MG = Miller-Galante; PCA = porous-coated anatomic; PFC = press-fit condylar
Contemporary noncemented tibial designs have become more bone conserving with improved initial component stability with improved porous metal manufacturing for biologic fixation and prevention of tibial micromotion and subsidence. However, most modern second-generation TKA systems have recently become commercially available, and midterm and long-term outcome studies are needed for survivorship assessment.

Enhanced highly cross-linked polyethylene for the patella articulating surface and liner inserts, along with better tibial baseplate locking mechanisms, have markedly mitigated catastrophic polyethylene wear and osteolysis seen with conventional polyethylenes. Noncemented patella designs incorporated a solid barrier layer between the porous surfaces that allows for smaller metal-backing and greater polyethylene thickness. Furthermore, newer materials, such as porous tantalum, porous titanium, and hydroxyapatite (HA), manufacturing through plasma spray or three-dimensional (3D) printed technology, have led to superior immediate rigid mechanical fixation and ultimate biologic osseointegration. Modern noncemented TKA systems are summarized in Table 2.

Patient Selection
Adequate bone quality is critical for noncemented TKA stability and osseointegration. Aside from grossly osteoporotic bone on plain radiographs, it may be difficult to assess bone quality objectively via routine preoperative imaging. Generally, younger, active, and obese patients with good bone quality are good candidates. However, the final decision is generally determined after intraoperative bone evaluation. Intraoperative bone quality assessment is a qualitative assessment per the surgeon based on a number of factors. Sawing the bone with ease, manual palpation of the cancellous bone, and fit of the trials can help determine bone quality. Intraoperative assessment is matched to patient demographics and preoperative radiographs for a global bone quality assessment. Contraindications for noncemented TKA include elderly patients with osteoporotic bone or with compromised bone vascularity.

Surgical Technique
Bone Preparation
Although cementation can accommodate imperfect bony cuts, defects, and bone quality, noncemented fixation requires maximum rim fixation to allow ample surface area for osseointegration. The preparation of dense sclerotic bone can cause the saw blade to skive and adversely affect flush surfaces cutting. Sclerotic bone may further generate excessive heat, which may lead to thermal necrosis. Saw blade irrigation may reduce thermal effects, along with meticulous saw technique. Uneven bone cuts can also cause gapping and increased micromotion at the implant-bone junction. Excessive micromotion has a greater risk of fibrous integration, progressive radiolucency, subsidence, loosening, and/or instability. It is important to confirm an adequate tibial resection depth because under-resecting a varus knee, for example, can leave excessively hard subchondral bone on the medial plateau, resulting in a suboptimal bleeding bone for noncemented fixation (Figure 2). The tibial cut can be examined intraoperatively with the “four corners test” described by Witmer and Meneghini (Figure 3).

Implantation
Unlike with cementation, a dry bony surface is not needed with noncemented implantation. Adequate resected bony surface protection until final components implanted is the most important aspect of noncemented bony preparation. Careful attention is needed during placing and removing trial implants, spacer blocks to check gaps, and posterior capsular osteophyte removal. Any unequal bony compression or iatrogenic defects can markedly alter implant stability.

Femoral Implant implantation requires careful inspection to ensure adequate final placement because there is a tendency for implant flexion relative to the long axis of the femur during impaction because of the initial contact of the longer anterior condyle on the anterior bone. Frictional resistance from the porous coating also creates a tendency for the surgeon’s hand to drop toward the table, creating further component flexion. This can result in an excessive gap between the anterior chamfer cut and implant. Using a captured femoral inserter mitigates this complication by maintaining a relatively extended component position. Unlike the tibia implant, small gaps less than 1 mm are generally acceptable anteriorly because it does not adversely influence implant fixation, given the femoral implants’ larger surface area and 3D press-fit geometry.

Final tibial impaction also requires scrutiny to ensure the baseplate and bony surface are colinear to optimize component press-fit (Figure 4). Implanting at an oblique angle can disrupt the interference fit in the prepared path within the cancellous bone. After the tibia is seated, the implant-bone interface is assessed to confirm that the
Table 2. Selected Modern-Design Noncemented Total Knee Arthroplasty Systems

<table>
<thead>
<tr>
<th>System</th>
<th>Manufacturer</th>
<th>Year</th>
<th>Porous Metal</th>
<th>Trademark</th>
<th>Design Features</th>
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| Attune  | DePuy Synthes      | 2019 | Ti           | Porocoat       | • The noncemented tibial baseplate features four peripheral porous-coated pegs around a proximally coated central cone  
• The pegs are designed to increase the press-fit surface area and stability of the component  
• The fully coated pegs move outward from the central cone because the size of the tibial base increases, which ensures increased rotational and axial support throughout all size ranges  
• The mediialized anatomic patella conforms with the trochlear groove with built in range up to 15 degrees freedom of rotation form its optimal position |
| Triathlon| Stryker            | 2014 | Ti           | Tritanium      | • Femoral and tibial baseplate design and locking mechanism same as cemented design  
• Tibial baseplate features four cruciform pegs with porous titanium undersurface  
• The noncemented CoCr femoral implant is coated with CoCr beads and available with and without adjunct hydroxyapatite coating  
• Metal-backed patella has 3D porous titanium with greater polyethylene thickness and smaller metal backing |
| NexGen  | Zimmer Biomet      | 1999 | Tantalum     | Trabecular Metal | • Monoblock and modular tibial baseplate design  
• Monoblock undersurface with porous tantalum with 2 hexagonal pegs with ultrahigh molecular weight polyethylene bearing surface  
• Modular design consisting of Ti alloy tray with porous undersurface tantalum layer. Also contains a small circular central peg in additional to two peripheral hexagonal pegs  
• Single tantalum peg on patella |
| Persona | Zimmer Biomet      | 2018 | Tantalum     | Trabecular Metal | • Bone conserving implant design with anatomic tibial baseplate  
• High flex femoral design with multiple polyethylene constraint designs  
• All tibial baseplates are modular noncemented designs with porous tantalum and 2 hexagonal pegs  
• Single tantalum peg on patella |
| Vanguard| Zimmer Biomet      | 2003 | Ti           | Regenerex      | • Rounded sagittal femoral profile  
• Deeper and swept-back trochlear groove  
• Longer and wide proximal trochlear groove for better patellofemoral kinematics  
• Porous plasma spray coating for porous titanium |
<p>| Evolution| MicroPort          | 2017 | Cancellous Titanium | BioFoam        | • BioFoam cancellous Ti acts as a biological scaffold to allow osteoblasts to form onto the Ti struts and induce angiogenesis through the interconnecting pores |</p>
<table>
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</tr>
</thead>
</table>
| GMK      | Medacta            | 2011 | Titanium     | Hydroxyapatite | • Medial pivot kinematics with the medial side of knee staying stable while the lateral compartment translating anterior and posterior according to tibial rotation  
• Constant radius femoral implant both in the sagittal and coronal plane with a highly conforming medial compartment and less conforming lateral compartment  
• No noncemented patella option |
| Truliant | Exactech           | 2020 | Ti           | —         | • Porous crushed bead coating on femur and tibia  
• Tibial design includes combination of porous pegs and channeled keel with flutes to improve bony-implant engagement and micromotion resistance  
• The integrated bone screw fixation option allows for additional stability  
• No noncemented patella option |
| EMPOWR 3D | DJO Global        | 2018 | Ti           | P²        | • Cruciform peripheral pegs provide initial component fixation and stability  
• Triflange bladed keel optimized for rotational stability |
| Klassic  | Total Joint Orthopaedics | 2016 | Ti | CoCr | Cobalt 3D™ | Ti-Coat® | • The Klassic Porous Femur features Cobalt 3D™, an ultraporous three-dimensional sintered porous coating  
• The femoral pegs are smooth to help prevent stress shielding and increase stabilization.  
• Femoral implant has a unique, patented trochlear groove that allows optimal patellar tracking along a 9° double Q-angle on both left and right anatomy, whereas retaining a neutral outside profile of the anterior flange.  
• The thin anterior flange incorporates a deepened trochlear groove that eliminates the need for a bone sacrificing and time-consuming fifth cut and bone preparation for the anterior notch  
• The Klassic Porous Tibial Baseplate features Ti-Coat®, an ultraporous, three-dimensional sintered porous coating  
• The pegs are smooth to help prevent stress-shielding and increase stabilization; the pegs also allow for an incremental amount of press-fit  
• No noncemented patella option |
Porous metal undersurface is in direct contact with the underlying host bone.\textsuperscript{21}

Most surgeons prefer a free-hand patella cutting technique.\textsuperscript{21} Vigilant patella preparation is needed to make a flat cut. It is important to impact the patella uniformly so that there are no bone-implant interface gaps. Because the residual patella host bone is generally 12 to 14 mm, excessive compression can cause iatrogenic fracture.

Robotic-Assisted TKA

Traditional surgical technique and bony cuts for noncemented TKA rely on anatomical landmarks and available implant geometry. Reliable noncemented fixation is contingent on precision bone cuts that limit bone-implant gaps to help achieve stable initial mechanical fixation. However, bone cuts using conventional guides, instruments, and a traditional oscillating saw can result in errors in cuts ranging up to 1.1° in varus-valgus and up to 1.8° in flexion-extension planes.\textsuperscript{22} These cutting errors can result in bone-implant gaps that can delay bone ingrowth into noncemented implants.\textsuperscript{22} Robotic semiactive and active technology may mitigate these complications by improving the precision and accuracy of the bony cuts for a uniform bone-implant interface. However, midterm and long-term time studies are needed to determine the effect of robotic assistance on noncemented TKA survivorship compared with manual noncemented and robotic/manual cemented techniques. Furthermore, in today’s value-based cost-conscious healthcare environment, the prospect of robotic-assisted TKA depends markedly on the consideration of quality of care relative to cost. Robotic technology presents with substantial upfront and maintenance expenditure in addition to preoperative imaging, increased operating times during the learning phase, and platform updates.\textsuperscript{23} Widespread incorporation of new technologies should be coupled with the anticipated long-term outcomes and reduced complications beyond the robotic technology cost.

Manufacturing

Porous Metals

Porous metals are a three-dimensional cellular metal structure with interconnected pores. Porous metal exhibits lower but sufficient stiffness (0.8 to 2.0 GPa)\textsuperscript{24} compared with solid metal, with a modulus of elasticity near cortical bone (from 0.4 GPa of trabecular bone to 17.9 GPa of cortical bone).\textsuperscript{25} Although older porous-coating demonstrated adequate clinical results, the first-generation porous metals had low volumetric porosity, suboptimal frictional characteristics, and markedly higher modulus of elasticity relative to host bone.\textsuperscript{26}

Newer porous metals, such as tantalum and Ti, have enriched press-fit characteristics with improved osseointegration ability compared with first-generation noncemented implants. These surfaces are rougher, allowing better initial press-fit and stability and greater bony ingrowth from higher porosity. Biologic fixation is optimized with pore size 500 to 600 μm and 60% to 65% overall porosity.\textsuperscript{27} These properties decrease gap spaces between the bone and prosthesis and increase the implant friction surface which decreases micromotion (goal <150 μm) and further stimulates osseointegration.\textsuperscript{27}

Porous tantalum Trabecular Metal (Zimmer Biomet) is a highly porous biomaterial with biocompatibility, corrosion resistance, and high coefficient of friction (Figure 5). Porous tantalum’s coefficient of friction (0.88 to 0.98) on cancellous bone is markedly greater than older noncemented TKA materials that included porous sintered beads (0.50 to 0.66).\textsuperscript{28} Tantalum’s modulus of elasticity (2 to 20 GPa)\textsuperscript{29} is between cortical and cancellous bone, which is notably lower than Ti and CoCr.\textsuperscript{28} This likely creates a more physiologic stress transfer at the bone-implant interface.

Analogous to tantalum, porous titanium (OsseoTi, Zimmer Biomet; Tritanium, Stryker) serves as an osteoconductive scaffold encouraging osteoblast migration for bony ingrowth. The average pore size and
overall structure have been engineered to mimic cancellous bone. OsseoTi is a highly porous Ti6Al4V alloy, with an average pore size of 475 μm, porosity of 69%, and a low modulus of elasticity between 2.8 to 3.7 GPa, which is comparable with subchondral bone. Tritanium is a highly porous, open-cell, 3D surface using CPTi powder. To mimic bone structure closely, Ti alloys form highly interconnected, open-cell structures that allow eventual bony growth. Tritanium architecture is derived from reticulated polyurethane foam with an additive surface CPTi layer that is placed on a Ti substrate and laser sintered in a vacuum. The resultant material is then volatilized, rendering a 3D-CPTi structure followed by a series of powder coating until the final pore size design is achieved. The final Tritanium material has 70% porosity and consists of interconnecting minor (311 μm) and major pores (546 μm) (Figure 7). Additive manufacturing (AM), as used with OsseoTi and Tritanium, can create solid, porous, or fenestrated materials on implants, which generally cannot be accomplished through conventional manufacturing. This technology can optimize ingrowth metal porosity and the ability to manufacture a variety of complex geometries.

Figure 3

A, Photograph showing ensuring a planar distal femoral cut with a saw blade. B, “4-Corner Test” attempting to rock tibial baseplate on the cut surface to assess the planar accuracy of the tibial cut. C, Schematic illustration of the Four Corners Test. (Adapted with permission from Witmer D, Meneghini R: Cementless total knee arthroplasty: Patient selection and surgical techniques to optimize outcomes. Seminars in Arthroplasty 2018;29:50-54.) Schematic illustration adapted from Cleveland Clinic Foundation. Adaptations are themselves works protected by copyright. So, to publish this adaptation, authorization must be obtained both from the owner of the copyright in the original work and from the owner of copyright in the translation or adaptation.
Similar to OsseoTi and Tritanium, newer porous titanium designs are being introduced, including BioFoam (Microport Orthopedics, Inc) and Regenerex (Zimmer Biomet). Newer ingrowth Ti designs have focused on improving cancellous Ti compatibility with bone that functions as a biologic scaffold to allow faster bone ingrowth (up to 80% porosity). The pore size averages 530 μm with interconnecting pore diameters of 200 μm with ingrowth reported in canine studies as early as two weeks. Limited data are available, however, regarding the efficacy, clinical outcomes, and longevity of these newer porous titanium designs. A comprehensive list of porous metal characteristics of noncemented TKA surfaces is summarized in Table 3.

**Hydroxyapatite**

Bioceramics such as HA are osteoconductive and offer clinical advantages over simple porous metal coating, including bony ingrowth acceleration and biological fixation compared with porous coating alone and early bony ingrowth in the presence of small gaps or initial instability. A prospective study of 1,000 patients implanted with a noncemented HA-coated TKA, Active
Noncemented Knee (Australian Surgical Design and Manufacture Pty Ltd), found 99.1% 10-year cumulative survival with revision as the end point. Tai and Cross prospectively evaluated 118 HA-coated non-cemented TKA in young patients (younger than 55 years) and found an overall 97.5% rate of implant survival (excluding polyethylene exchange) and 92.1% (including polyethylene exchange) at 12 years. Older patients (older than 75 years) have shown similar functional improvements and survivorship compared with younger individuals undergoing HA-coated non-cemented TKA.

Plasma Spray

Plasma spray coating on Ti alloys is a viable alternative to sintered beads or diffusion-bonded metal ingrowth surfaces. The plasma spray process allows the Ti alloy component to retain 90% of its fatigue strength, as opposed to less than 50% for sintered and diffusion-bonded methods commonly used in first-generation noncemented TKA implants. After early failures because of poor mechanical design, adding a porous metal powder layer by thermal plasma spray became popular because of its cost effectiveness and longevity.

3D-Printing

Unlike conventional computer machining, where a large block of material is fashioned to shape a 3D object, additive layer manufacturing (3D-printing) constructs objects by fusing material together, layer by layer. This technology, although costlier than traditional computer machining or newer plasma spray coating, has gained popularity because of its time-efficient method of producing complex 3D products. Most modern noncemented TKA designs are manufactured using 3D-printed tantalum/Ti or plasma sprayed Ti/HA.

Clinical Outcomes

Noncemented TKA designs offer several theoretical benefits, including shorter operating room time, bone stock preservation, biologic integration, ease of revision, and elimination of other complications associated with cemented fixation including third body wear and loose fragments. Loosening in cemented implants is characterized by progressive linear radiolucency along the cement-bone junction. Although noncemented TKA can also have radiolucency at the implant-bone interface, lucency is generally nonprogressive, and osteolysis in older designs typically demonstrated a metaphyseal expansive pattern without component fixation interference. Newer-generation noncemented designs have shown improved osseointegration compared with first-generation systems. Hybrid fixation, which combines a cemented component (generally tibia and/or patella) with a noncemented implant (generally femur) has been proposed as an alternative fixation strategy to avoid complications of subsidence and failure. Yang et al performed hybrid fixation technique using five knee systems, with reported survival rate of 95%
(10 years) and 92% (15 years). Other authors found no benefit of cement compared with hybrid fixation at short- or mid-term follow up with comparable survivorship and outcomes.35 There is limited data, however, comparing hybrid fixation and modern fully noncemented TKA.

Several recent studies have compared the survivorship of cemented versus full noncemented TKA, with promising results for modern noncemented designs. In a retrospective study comparing similar cemented and noncemented primary designs, Miller at al37 reported porous titanium noncemented TKA aseptic loosening rate of 0.5% versus 2.5% aseptic failure rate in a matched cemented cohort at a mean of 2.4 years. Prospective randomized trial of cemented and noncemented TKA of the same design found no difference in pain, functional outcomes, Forgotten Joint score, implant subsidence, and survivorship at the 2-year follow-up.38 Another retrospective study compared similar cemented and porous Ti noncemented posterior stabilized modern designs in morbidly obese patients (mean body mass

**Figure 7**

A. Photograph showing the cancellous bone characteristics: average pore diameter of cancellous bone = 1 mm, average porosity of cancellous bone = 50% to 90%. B. Tritanium material characteristics: randomized pore sizing designed to mimic cancellous bone; mean pore size range = 400 to 500 μm, interconnected pore structure from end plate to end plate with mean porosity range = 55% to 65%. (Adapted from Stryker Orthopedics, Mahwah, NJ.) Adaptations are themselves works protected by copyright. So, to publish this adaptation, authorization must be obtained both from the owner of the copyright in the original work and from the owner of copyright in the translation or adaptation.

**Figure 8**

Anteroposterior and lateral radiographs demonstrating noncemented primary total knee arthroplasty at the 5-year follow-up without any signs of radiolucency, subsidence or loosening of femoral, tibial, and patellar components.
index (BMI 45 kg/m²) and found lower overall revision rate and revisions for aseptic loosening compared with the cemented cohort (5.4%, 0.9% vs. 25.9%, 11.8%, respectively) at the 5-year follow-up (Figures 8 and 9).³⁹

Noncemented TKA has also been effective in a younger cohort. In a review of 29 patients (mean age 45 years) undergoing noncemented TKA, an overall implant survivorship of 100% at 4 years was observed.⁴⁰ Kammath et al.⁴¹ prospectively studied 100 press-fit TKA

Figure 9

Chart showing the Kaplan-Meier survival curve of primary total knee arthroplasty (TKA) in morbidly obese patients with aseptic loosening as the end point. (Adapted with permission from Sinicrope BJ, Fehrer AW, Bhimani SJ, et al: Increased survivorship of cementless versus cemented TKA in the morbidly obese. A minimum 5-year follow-up. J Arthroplasty 2019;34:309-314.) Adaptations are themselves works protected by copyright. So, to publish this adaptation, authorization must be obtained both from the owner of the copyright in the original work and from the owner of copyright in the translation or adaptation.

Figure 10

Radiolucenties analyzed following the Knee Society criteria and the modification proposed for noncemented pegged tibial components. A, The implant-bone interface zones are shown in this anterior-posterior (AP) view of a stemmed cemented tibial component. B, The zones are shown in a lateral view of the stemmed cemented tibial component. C, The implant-bone interface zones are shown in the AP view of the noncemented tibial component. D, The implant-bone interface zones are shown in a lateral view of the noncemented tibial component. (Adapted with permission from Fernandez-Fairen M, Hernandez-Vaquero D, Murcia A, Torres A, Llopis R: Trabecular metal in total knee arthroplasty associated with higher knee scores: a randomized controlled trial. Clin Orthop Relat Res 2013;471:3543-3553.) Adaptations are themselves works protected by copyright. So, to publish this adaptation, authorization must be obtained both from the owner of the copyright in the original work and from the owner of copyright in the translation or adaptation.
patients with tantalum monoblock tibias and 312 cemented controls in young patients (younger than 55 years) and found no differences in perioperative outcomes, functional outcomes, complication rates, or cost. At the 5-year follow up, three complications were noted in the noncemented group unrelated to fixation failure. DeFrancesco et al42 found no progressive radiolucencies with improvement in KSS function at a mean of 10 years.

Radiolucent lines (RLL) following both cemented and noncemented TKA are concerning for osteolysis and loosening (Figure 10). Older noncemented implant designs have previously demonstrated early tibial and metal-backed patellar component failure with higher incidence of progressive RLLs ranging from 13% to 32.6% in tibial implants and up to 56.5% in HA-coated femoral noncemented components.43 At an average follow-up of 9.6 years, with an average BMI of 34.1 kg/m², Costales et al43 found most RLL under the tibial baseplate and femoral anterior chamfer. Most RLL were less than 2 mm and resolved by one year postoperatively. The authors suggested that there may be no association between the presence of RLL and long-term follow-up function in patients with modern porous-coated noncemented TKAs.43

Cost Analysis

Although noncemented implants have the potential for improved fixation survivorship and decreased rates of

Table 3. Metal Characteristics of Noncemented TKA Surfaces

<table>
<thead>
<tr>
<th>Porous Metal</th>
<th>Manufacturer</th>
<th>Porosity</th>
<th>Cell Size (^a)</th>
<th>Inter-Connecting Pore Size</th>
<th>Material</th>
<th>Bioactive Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>CsTi</td>
<td>Zimmer Biomet</td>
<td>52%-58%</td>
<td>480-560 (\mu)m</td>
<td>400-500 (\mu)m</td>
<td>Ti</td>
<td>N/A</td>
</tr>
<tr>
<td>Trabecular Metal</td>
<td>Zimmer Biomet</td>
<td>80%</td>
<td>500-550 (\mu)m</td>
<td>230 (\mu)m</td>
<td>Tantalum</td>
<td>N/A</td>
</tr>
<tr>
<td>Sintered Beads</td>
<td>Wright Medical Technology Stryker DePuy-Synthes Smith &amp; Nephew Total Joint Orthopaedics</td>
<td>30%-40%</td>
<td>N/A</td>
<td>N/A</td>
<td>Ti CoCr</td>
<td>HA coating</td>
</tr>
<tr>
<td>Fiber Mesh</td>
<td>Zimmer Biomet</td>
<td>50%</td>
<td>N/A</td>
<td>N/A</td>
<td>Ti</td>
<td>N/A</td>
</tr>
<tr>
<td>Ti Foam</td>
<td>Wright Medical Technology MicroPort Orthopedics</td>
<td>65%-75%</td>
<td>530-680 (\mu)m</td>
<td>250-300 (\mu)m</td>
<td>Ti CoCr</td>
<td>N/A</td>
</tr>
<tr>
<td>Porous Ti</td>
<td>Zimmer Biomet Stryker DePuy-Synthes Smith &amp; Nephew Exactech DJO global</td>
<td>55%-75%</td>
<td>100-700 (\mu)m</td>
<td>400-600 (\mu)m</td>
<td>Ti</td>
<td>Macroporous titanium</td>
</tr>
</tbody>
</table>

HA = hydroxyapatite; N/A = not applicable; TKA = total knee arthroplasty

\(^a\)Cell size describes the average diameter of a pore cell.
aseptic revision, noncemented TKA systems are considerably more expensive than cemented prostheses. However, most comparisons do not consider the additional cement cost, including operating room time and cement equipment/material. The estimated cost of one minute of operating room time in the literature ranges from $30 to $60.44 A cost-comparison study by Lawrie et al44 determined the average operating room time cost was $2,894 for noncemented TKA and $3,406 for cemented TKA. Furthermore, the average total cost of noncemented TKA was $7,553. Using the cheapest cementing technique with two bags of plain cement and a manual mixing bowl with spatula, the cost of a cemented TKA was $7,114.44

Similarly, when comparing noncemented and cemented TKA, Yayac et al45 found noncemented TKA to have higher implant costs ($3,047.80 vs. $2,808.73) but lower supply costs ($639.49 vs. $815.57) and lower operating room personnel costs ($982.01 vs. $1,238.26). The authors found that noncemented TKA systems did not markedly increase total procedural costs when compared with cemented implants. The increased noncemented prosthesis cost may be recuperated with savings in cost of cement, cement accessories, and shorter surgical times.

**Future Direction**

Additive manufacturing and 3D printing have revolutionized porous metal processing. These techniques may also have an economic advantage because smaller amounts of bulk material are needed for product assembly and by reducing the waste inherent with subtractive manufacturing.30 As TKA noncemented design continue to evolve, implant longevity will continue to be dependent on further advancement of porous ingrowth material. Vendors such as 4WEB Medical use proprietary 3D-truss technology based on “topological dimension theory” that is the basis of noncemented platforms (Figure 11), with FDA clearance in spinal devices.30 Forthcoming development involves application of this technology to improve the quality of hip and knee fixation at the implant-bone interface and to reduce the amount of bone removed during preparation.30 Future next-generation noncemented designs may integrate enhancements at interface surfaces involving nanotexturing, different metal substrates, and antimicrobial layering to avert bacterial adhesion and biofilm growth.

**Summary**

Noncemented TKA technology for biological fixation has evolved from first-generation porous coatings to the use of highly porous metals. The intermediate to long-term radiographic and clinical performance of contemporary noncemented TKA has been excellent, with performance that equals or exceeds that of cemented fixation. More prospective, randomized trials, along with registry data, are needed to clearly delineate differences between fixation types, long-term survivorship, and patient functional outcomes between these fixation strategies.

**References**

References printed in bold type are those published within the past 5 years.

Levels of evidence are described in the table of contents. In this article, references 3, 17, and 38 are level I studies. Reference 31 is level II study. References 1, 5, 6, 11, 12, 13, 18, 37, 39, 41, 42, 44, and 45 are level III studies. References 4, 7, 8, 9, 10, 16, 27, 32, 33, 36, 40, and 43 are level IV studies. References 2, 14, 15, 19, 20, 21, 22, 23, 24, 25, 26, 29, 30, 34, and 35 are had no level of evidence.


