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Implant Surface Technologies to Promote Spinal Fusion: A Narrative Review

ANDREW J. CROFT, MD[1]; HANI CHANBOUR, MD[2]; JEFFREY W. CHEN, BA[3]; MASON W. YOUNG, MD[1]; AND BYRON F. STEPHENS, MD, MSCI[1,2]

[1]Department of Orthopedic Surgery, Vanderbilt University Medical Center, Nashville, TN, USA; [2]Department of Neurological Surgery, Vanderbilt University Medical Center, Nashville, TN, USA; [3]Department of Neurological Surgery, Vanderbilt University School of Medicine, Nashville, TN, USA

ABSTRACT

The technology surrounding spinal fusion surgery has continuously evolved in tandem with advancements made in bioengineering. Over the past several decades, developments in biomechanics, surgical techniques, and materials science have expanded innovation in the spinal implant industry. This narrative review explores the current state of implant surface technologies utilized in spinal fusion surgery. This review covers various types of implant surface materials, focusing on interbody spacers composed of modified titanium, polyetheretherketone, hydroxyapatite, and other materials, as well as pedicle screw surface modifications. Advantages and disadvantages of the different surface materials are discussed, including their biocompatibility, mechanical properties, and radiographic visibility. In addition, this review examines the role of surface modifications in enhancing osseointegration and reducing implant-related complications and, hopefully, improving patient outcomes. The findings suggest that while each material has its potential advantages, further research is needed to determine the optimal surface properties for enhancing spinal fusion outcomes.

Focus Issue Article

Keywords: spinal fusion, spinal implants, surface technology, interbody, pedicle screw

INTRODUCTION

Spine surgery has been greatly transformed by continual improvements in biomechanics and engineering. Optimizing the development of solid arthrodesis with enhanced implant surface properties has become an area of growing interest over the past decade. While it remains the standard to use spinal instrumentation with rods and screws for cervical and thoracolumbar pathology, it is still within recent memory that these implants were unavailable for spine surgeons.[1] In 1891, Dr. Berthold Earnest Hadra attempted to treat a patient with Pott's disease suffering with progressive neurological decline from a fracture dislocation of the cervical spine by wiring together the sixth and seventh cervical vertebrae for stability.[2] In the early 1910s, Drs. Russell Hibbs and Fred Albee continued to develop the nascent field of spine surgery by laying down the spinous process autograph along the interspinous space to promote fusion in a pediatric patient with a severe kyphotic deformity.[3] The next leap forward came in 1958 when Dr. Paul Harrington introduced the first successful implantable spinal instrumentation system, the Harrington Rod, a laminar hook and rod system designed to treat polio-related neuromuscular scoliosis.[4] Building on this innovation, Drs. Yves Cotrel and Jean Dubousset developed the Cotrel–Dubousset instrumentation system in 1978, a dual-rod system with multiple fixation points using hook and rod combinations, allowing for 3D correction of the spine.[4]

With the development of modern pedicle screw systems, interbody devices, and osteoinductive and osteoconductive bone grafts, the ability to achieve solid fusion has advanced significantly. Alloying titanium with other metals or creating polyetheretherketone (PEEK) composites and alternative cross linking are methods that can alter the material's intrinsic mechanical properties. Recently, there has been increasing interest in understanding how these implantable materials interact with native spinal bony tissue. In this narrative review, we sought to (1) summarize the current state of implant surface technology and (2) describe the impact of implant surface technology on bone fusion.

INTERBODY IMPLANTS

A critical component of an interbody implant is choosing the implant material, which must have sufficient mechanical strength to bear compressive forces, particularly in the lumbar spine, where it will be subject to repetitive and constant compressive forces across the interbody space. At the same time, implants must resist shear and axial rotation forces. The material should also ideally have a similar elastic modulus, also known as Young's modulus, to that of native bone. A material's elastic modulus is the ratio of stress to strain and is often used to quantify a material's stiffness.[5] Native cortical bone possesses a Young's elastic modulus of 18 GPa, whereas cancellous and trabecular bones have elastic moduli of 2 and 3–4 GPa, respectively.[6] To put these values into perspective, the 2 most common implant materials are titanium and PEEK, which have elastic moduli of 102–110 and 3–4 GPa, respectively.[7] In native tissues, the presence of surface chemical and protein markers signals cells to adhere and grow. Similarly, the reaction of bony tissue to an implant is dictated by material surfaces.[8–10] As such, the field of implant technology has given greater focus on modification, functionalization, and bioactivation of surfaces to improve osseointegration.

TITANIUM

Ti-6Al-4 V alloy is a commonly utilized metal alloy for spinal interbody devices in large part due to its ability to form a titanium dioxide (TiO_2) surface layer that shows resistance to corrosion and can facilitate bone growth in and around the implant.[11] Other implant surface properties, such as surface roughness and topography, have also been shown to impact activity at the cell–material interface, thereby affecting the formation of new tissue.[12] The surface of titanium (Ti) implants can therefore be modified to influence the way native tissues interact with the implant to improve both on-growth and in-growth of bone. On-growth of bone is the direct apposition of bone onto the surface of the material, while in-growth involves the interlocking or growth of bone into a porous surface of a material.[11]

On-Growth

A particularly useful surface modification to achieve bone on-growth is surface roughening. At a basic level, surface roughening helps improve initial fixation of implants and helps limit motion through simply increasing the static friction between the implant surface and bone.[13,14] Surface roughening not only increases initial bony adhesion but is also known to induce differentiation and phenotypic maturation of osteoblasts, resulting in increased osteointegration and bone formation.[15–17] Even when unmodified, surface-roughened titanium without the addition of bone graft has been shown by Krayenbuhl et al[18] and Kroppenstedt et al[19] to be able to achieve successful cervical and lumbar fusion. When compared with smooth Ti, roughened Ti has been shown to stimulate higher local levels of bone morphogenic proteins, osteoclast inhibitors like transforming growth factor beta (TGF-β) and osteoprotegerin, as well as promotors of angiogenesis including fibroblast growth factor 2, vascular endothelial growth factor A, and angiopoietin-1.[20] These effects can occur with surface roughening at both the micro- and nanoscales. At the microscale, roughened Ti spine implants often have roughness sizes ranging from 3 to 30 μm, depending on the manufacturer.[21,22] For comparison, cementless total hip stems typically have an on-growth segment with a roughness size ranging from 3 to 8 μm.[23,24] Alternatively, innovations in spinal fusion sciences has taken Ti roughening down to the nanoscale (10^{-9} m), better mimicking the architecture of natural tissues and providing host cells the ability to interact with implants on a molecular level through direct interactions with cell membrane receptors.[20,25] While studies show positive effects from the nanostructures alone in terms of osteointegration and bone formation, there is also believed to be a synergistic effect when combined with microrough surfaces.[16]

In-Growth

Titanium alloy can be machined to achieve a higher degree of porosity and interconnectivity, thereby promoting bone in-growth. One of the challenges of titanium is its relatively higher elastic modulus compared with that of native bone, which can lead to stress shielding and subsequently progress to subsidence, interspace collapse, and bone atrophy.[5,11] On a macroscale, increasing the porosity reduces the elastic modulus, bringing it closer to that of native bone or PEEK, reducing the subsidence issues seen with early titanium alloy and nonporous titanium cages.[11,26] Studies have also demonstrated increased osteoblast adhesion, proliferation, and differentiation in porous titanium cages compared with nonporous cages, attributable to the porous structure mimicking trabecular bone and allowing for osteoblast migration.[26,27] Additionally, Ti cages with bulk porosity have been shown to have significantly superior load sharing properties than their nonporous Ti cage counterparts.[28] Fujibayashi et al,[29] in their prospective trial, used a porous titanium cage for transforaminal lumbar interbody fusion. The authors found that all 5 cases achieved bony fusion by 6 months. At 12 months, the authors did not find evidence of subsidence, which was thought to be attributed to the lower elastic modulus, with a subsequent lower chance of subsidence and higher rate of osseointegration due to surface modification as contributors to the success rate.[29] Wu et al[30] designed an even more porous titanium interbody cage with full interconnectivity using electron beam melting in sheep models. This particular design demonstrated superior bony in-growth with less micromotion relative to a PEEK alternative. One area of potential concern with the porous design is the increased risk of wear debris, which is caused by a decrease in the surface contact area at the implant–bone interface. This leads to pressures and increasing the likelihood of mechanical wear leading to debris formation.[26,31]

Chemical Modification—Hydroxyapatite

Another benefit of TiO_2 is its ability to generate negatively charged hydroxide ions (OH^-) when exposed to humid environments.[32] These hydroxide ions can bind to calcium (Ca^{+2}) and phosphate (PO_4^{-3}) ions, forming a bone-like appetite and stimulating osteoblastic activity.[32] This property can be advantageous by coating titanium with hydroxyapatite (HA). HA can be sintered at high temperatures[33] or deposited as a plasma spray[34] apatite layer that mimics the bone surface, allowing for chemical integration when implanted. While HA-modification has not been extensively studied in titanium interbody spacers, it has been shown to enhance osseointegration of other spinal hardware such as pedicle screws and has also been shown to enhance osseointegration of other orthopedic implants.[35–37]

PEEK

PEEK spinal cages were originally developed in the late 1980s by a polymer engineer, Carl McMillin, and were first implemented in the early 1990s by Brantigan et al.[38,39] PEEK cages are widely used today as surgical implants due to their excellent mechanical strength, elastic modulus similar to that of bone, biocompatibility, and ease of manufacturing.[40] Another major advantage of PEEK over titanium is its radiolucency, which makes PEEK particularly useful in monitoring for implant migration and for accurate assessment of fusion postoperatively.[5] Although it possesses an elastic modulus profile closer to native bone than that of traditional solid titanium, it lacks osseointegrative properties.[15] This is largely attributable to the hydrophobic nature of untreated PEEK, which renders it bioinert and unable to bond to bone and achieve solid fusion.[41] As a result, research has shown that PEEK implants may be associated with cage migration and pseudarthrosis.[5] To enhance bony growth with PEEK implants, multiple methods have been explored.

Composites

One of the primary methods developed to improve the effectiveness of PEEK implants was the implementation of PEEK composites, in which PEEK is combined with a more biologically active material. In an in vivo and in vitro study, Wu et al[42] found that an n-TiO2/PEEK composite resulted in significantly more bone volume compared with PEEK alone. In an ovine lumbar model, McGilvray et al[43] found that PEEK-titanium composite implants resulted in a significant decrease in the range of motion following implantation. In addition to Ti-containing PEEK composites, PEEK has also been impregnated with other materials such as HA in an attempt to more closely mimic bone. In sheep cervical fusion models, Walsh et al found that incorporating HA directly into the PEEK matrix resulted in increased direct bone apposition, concluding that the HA-PEEK composite provided a more favorable environment than PEEK alone for bone on-growth.[40]

Coatings

Another breakthrough was the use of various biologically active coatings for PEEK implants, a method often used to augment composite materials. The 2 major composite and coating pairings were Ti and HA. Since natural bone is a composite of fine HA reinforced on a network of collagen, a biocompatible PEEK scaffold with HA particles would theoretically be capable of supporting bone growth to mimic normal bone. Other metals were introduced in small quantities to modulate the mechanical properties of coating. Wong et al introduced a strontium-containing HA and PEEK composite to create an elastic modulus similar to that of cortical bone (9.6–10.6 GPa).[44] Other potential composites with PEEK that have been explored include calcium silicate and β-tricalcium phosphate, among others.[45,46] Most findings, however, were purely related to osseointegrative properties in animal studies with a substantial lack of clinical trial data.[47] Titanium composites and coatings offer mechanical improvements along with significantly enhanced osseointegration. Han et al applied a coating of Ti to PEEK with electron beam deposition and found improved cell proliferation as well as greater bone contact following implantation.[48] HA in addition to Ti applied by plasma spray onto a PEEK implant has also demonstrated a promising mechanical adhesive strength.[49] These findings suggested that PEEK composite implants and biologically active coatings may be promising approaches to enhance the osseointegrative properties of PEEK cages in interbody fusion procedures. Although bioactive treatments have shown potential advantages and demonstrated a great deal of promise, most are not readily available for clinical application yet because most studies have been conducted in animal models.[50] Additional barriers to the use of these products are their highly specialized manufacturing demands, increased cost, altered physical properties, or simply because they have not been fully characterized for use in humans.

Porous PEEK

While PEEK composite materials and coatings have shown improvements in osseointegration, an alternative approach has also been developed by implementing the concept of porosity originally utilized in titanium implant modifications.[51] Designed to mimic the structure of human trabecular bone, early generation porous PEEK cages have demonstrated both a greater expulsion resistance compared with smooth PEEK cages and a greater adhesion strength compared with plasma-sprayed Ti-coated PEEK surfaces. In vitro studies have confirmed that porous PEEK is able to facilitate cell attachment, proliferation, and osteogenic differentiation of multiple bone cell lineages as well as enhance mineralization at the cellular level in a manner similar to roughened and porous titanium surfaces. At the implant level, in vivo animal studies have shown comparable bone in-growth into porous PEEK as those previously reported for porous titanium, leading to twice the fixation strength of smooth PEEK implants.[51–55]

OTHER IMPLANT SURFACES

Many other possible implant materials are currently under consideration. Silicon nitride and tantalum are 2 commonly discussed surfaces. Silicon nitride is a non-oxide ceramic with osteoconductive properties similar to porous Ti; it not only demonstrated promising high mechanical properties and a wear-resistant profile but also exhibited partial radiolucency and a high fracture resistance.[56–58] While implants have been designed, the interbody cages made of silicon nitride have not been fully explored.

Tantalum is a metal with a high compressive strength. Porous tantalum has demonstrated good osseointegration after treatment with alkali and heating.[59] Animal studies have shown that tantalum implants were a better bridge between autograft bone and native vertebral bone compared with PEEK implants.[60,61] In a randomized controlled human trial, trabecular tantalum cervical implants without graft were compared with tricortical iliac crest autograft and plating in one-level anterior cervical discectomy and fusion.[62] Although the findings were not statistically significant, the results showed slightly higher rates of radiographic fusion in the tantalum implant group at both 6 and 12 months postoperatively.

PEDICLE SCREWS

Much like the advancements made in implant surface technology, large strides have also been made in the surface technology of instrumentation components, particularly in pedicle screws. While posterior instrumentation with traditional titanium or stainless steel pedicle screws has been shown to increase fusion rates, pedicle screw loosening remains a significant complication, with loosening rates reported to range from 0.6% to 11%.[63,64] The risk of loosening is even greater in patients with osteoporosis, with an incidence reported as high as 60%.[65,66] Pedicle screw loosening can lead to further issues such as pain, rod or screw breakage, pseudarthrosis, and loss of spinal alignment.[67] Given the aging population and the increasing requirements for spine surgery with posterior instrumentation, much attention has been devoted to augmenting the surface material of pedicle screws to optimize fixation.[68]

Roughened Titanium

Because roughened titanium interbody implants have been previously shown to improve interbody fixation, the same methodology has also been applied to pedicle screws in an effort to improve pullout strength. In an in vitro and in vivo study by Schwartz et al,[69] investigators compared untreated, smooth titanium screws to screws that were grit blasted to generate a rough, nanotextured surface. In the in vivo arm, after implanting the screws into sheep models, they found the roughened screws to have significantly greater pullout strength compared with the smooth screws. In the in vitro arm, they cultured human osteoblast-like cells on smooth and roughened titanium discs and found the roughened discs to have increased levels of growth factors and cytokines such as prostaglandin E2, transforming growth factor-β1, and osteoprotegerin, which promote osteoblastic activity and inhibit osteoclastic activity.[69]

Hydroxyapatite

Akin to its use in interbody surface augmentation, HA has also been extensively studied as a surface coating material for pedicle screws. When a titanium or stainless steel pedicle screw is coated with HA, the HA serves as a promotor of bone deposition along the screw surface.[63,67,70,71] In perhaps the first clinical study analyzing HA-coated screws in patients, Sanden et al compared implanted titanium screws in the lumbar spine with and without HA-coating in patients undergoing lumbar fusion and found that the HA-coated screws had significantly higher extraction torque postoperatively and a significant decrease in the incidence of loosening compared with noncoated screws.[71] Other studies using ovine and porcine animal models have also shown HA-coated pedicle screws to have a higher screw pullout force threshold compared with untreated pedicle screws.[67,70] They were also shown to have a superior osseointegration profile in canine and porcine osteoporosis models compared with untreated pedicle screws.[72,73] Despite this, concerns remain regarding when the inevitable need for revision surgery arises in the setting of well-integrated, HA-coated polyaxial pedicle screws.

Carbon Fiber-Reinforced PEEK

Due to the metal-induced artifacts produced by standard titanium alloy pedicle screws on postoperative imaging, carbon fiber-reinforced PEEK (CF/PEEK) pedicle screws have been developed.[74] Because both carbon fiber and PEEK are radiolucent and have no magnetic properties, CF/PEEK pedicle screws help to minimize artifacts seen on both computed tomography and magnetic resonance imaging, thereby permitting a more thorough and accurate postoperative assessment of images.[7,74,75] This feature plays an important role in detecting pseudarthrosis and adjacent segment disease and evaluating neural structures postoperatively.[74] Furthermore, the radiolucent feature of CF/PEEK pedicle screws can be of substantial benefit in spine tumor cases. The higher-quality images may help in dose calculations for radiotherapy planning. Additionally, CF/PEEK screws can also reduce the radiation scattering and tumor shielding caused by metallic implants.[75–77] In a cadaveric study by Lindter et al,[74] investigators found no differences between the nonmetallic CF/PEEK pedicle screws and standard titanium pedicle screws with regard to screw loosening when subjected to cyclic craniocaudal loading. However, CF/PEEK pedicle screws are yet to be widely adopted due to their high cost and less availability compared with titanium.[78]

Gold Nanoparticle Coating

Another relatively newer method of pedicle screw surface augmentation involves nanoparticle coating using metals such as gold or silver. Similar to the osseointegration exhibited by HA-coated pedicle screws, gold nanoparticles have also been shown to increase osseointegration when applied to implant surfaces.[79–81] Gold nanoparticles act as osteogenic agents by inducing osteogenic differentiation of progenitor cells and by inducing activation of the p38 mitogen-activated protein kinase signaling pathway.[79,82,83] The p38 mitogen-activated protein kinase pathway causes further upregulation of osteogenic genes essential for osteoblast differentiation, such as runt-related transcription factor 2 (RUNX2),[84] the gene that determines the osteoblast lineage from pluripotent mesenchymal stem cells.[83] Gold nanoparticles may be conjugated to the surface of titanium implants coated with 3-mercaptopropyl trimethoxysilane through gold–sulfur bonding.[79] In a study by Ko et al[79] using rabbit models, investigators demonstrated higher osseointegration parameters using pedicle screws doubly coated with gold nanoparticles compared with pedicle screws coated with HA. These findings suggest that implants coated with gold nanoparticles may be a valid alternative to HA-coated pedicle screws, particularly in patients with poor bone quality.

Silver Nanoparticle Coating

Silver nanoparticles can also be applied to the surface of pedicle screws, which is done either by silver plasma ion immersion or vapor deposition.[85] In addition to their biocompatible properties, silver nanoparticles have been shown to exert an antibacterial effect, which is achieved through the release of silver ions from soluble complexes, which generate reactive oxygen species that breakdown bacterial components.[20,86] In a study by Hazer et al, investigators demonstrated that silver-impregnated pedicle screws had an antimicrobial effect against methicillin-resistant *Staphylococcus aureus*, especially in the inhibition of biofilm formation, in the lumbar spines of rabbit models.[87] The latter may represent a useful aspect of silver nanoparticle coating as hardware infection can be a life-threatening complication of spinal surgery.[88]

CONCLUSION

In conclusion, implant surface technology has advanced significantly since the inception of the field. Substantial research in this area has led to a greater understanding of how various materials interact with native bone and tissue. In the field of spine surgery, interbody and pedicle screw surface materials play a crucial role in ensuring the success of spinal fusion procedures, and surgeons now have a range of options

Table. Advantages and disadvantages of implant surface technologies.

Surface Material	Advantages	Disadvantages
Interbody		
Titanium/HA-coated titanium/other surface-treated titanium	Strong biomechanical profile, biocompatible, and well studied	High stiffness increases risk of subsidence
Titanium-PEEK	Good fusion profile and radiolucent on imaging	Poor wear resistance, limited clinical data, and risk of delamination
PEEK	Radiolucent and biomechanical profile similar to native bone	Poor wear resistance, inferior fusion rate relative to auto/allograft, and fibrous scar formation
Silicon nitride	Low infection risk and good osseointegration	High cost, limited clinical data, and brittle
Tantalum	High fusion rate/biocompatibility	Radiopaque, difficult machining, and high cost
Pedicle Screws		
Roughened titanium	Improved osseointegration and pullout threshold	Lacking human clinical data
HA-coated screws	Improved osseointegration and pullout threshold	Lacking long-term randomized controlled trials
Carbon-fiber-PEEK	Radiolucent with reduced artifact in postoperative imaging	High cost and low availability; similar risk of loosening compared with traditional screws
Gold nanoparticle	Improved osseointegration	Lacking human clinical data
Silver nanoparticle	Decreased risk of infection	Lacking human clinical data

Abbreviations: HA, hydroxyapatite; PEEK, polyetheretherketone.

available to them (as summarized in Table) to enhance the integration of implants into surrounding tissues, reduce complications, and ultimately improve patient outcomes. Despite the advancements in this technology, the clinical data are relatively scarce and largely limited to laboratory studies or animal models. Long-term prospective clinical trials are required to further investigate the efficacy of these newer implant surface technologies. As researchers and surgeons continue to explore new options and refine existing techniques, we can expect to see continued advances in implant surface technology as additional research emerges.

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Corresponding Author: Byron F. Stephens, Department of Orthopaedic Surgery, Vanderbilt University, School of Medicine, 1215 21st Ave S, South Tower, Suite #4200, Nashville, TN 37232, USA; byron.stephens@vumc.org