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Review Article

Emerging Surface Coating Innovations for Orthopedic Implants: A Review

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Orthopedic implant technology continues to evolve through advances in surface engineering, particularly in the development of coating technologies designed to enhance implant integration, reduce infection, and mitigate inflammatory responses. Despite a vast array of literature and attention, growing scientific evidence does not support a clinically significant role for metal hypersensitivity in orthopedic implants. Instead, research has shifted to emerging surface treatments such as titanium nitride, oxide ceramics, and antimicrobial polymers that are engineered to improve osseointegration and resist microbial colonization. Coatings that incorporate non-eluting antimicrobial agents, smart stimuli-responsive materials, and wear-resistant ceramics show promising preclinical results, with some advancing to clinical trials. As these technologies mature, they may significantly reduce complications traditionally attributed to material biocompatibility and so-called metal allergy. This review examines recent literature on emerging advances in surface coating technology for orthopedic implants and the obstacles these technologies face in the journey towards clinical adoption. Hybrid implant modifications that target bacterial biology as well as colonization chemistry appear to be the next evolution of orthopedic implant coatings. Future research should prioritize validating long-term outcomes, optimizing coating durability, conducting cost-analysis surveys, and exploring pathways toward improved manufacturing.

INTRODUCTION

Orthopedic implant success relies on biocompatibility, mechanical integrity, and the ability of materials to integrate with host tissues while resisting infection (Wawrzynski et al. 2017). The notion of "metal hypersensitivity" is a poorly defined and largely unproven concept often invoked to explain adverse patient responses to metallic implant components without clear scientific justification (Wawrzynski et al. 2017; Scheidt, Schultzel, and Itamura 2019; Atwater and Reeder 2020; Lazarenko and Boiko 2022). The clinical significance of metal allergy reactions remains unproven and is increasingly viewed as speculative (Wawrzynski et al. 2017; Teo and Schalock 2017). Although patch testing

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and lymphocyte transformation testing (LTT) are used to evaluate suspected sensitivities, these tools lack standardization and offer limited predictive value in orthopedic patients (Gaillard-Campbell and Gross 2024; Yang et al. 2019; Bracey et al. 2022). Moreover, a growing body of evidence has shown no consistent relationship between metal sensitivity-related concerns and clinical outcomes (Bracey et al. 2022; Kotecki et al. 2023; Postler et al. 2018; Schmidt et al. 2019). Rather than centering on metal hypersensitivity as a relevant clinical and diagnostic concern, contemporary research emphasizes improving the biological interface between implant surfaces and host tissue. Emerging technologies- such as antimicrobial coatings, ceramic barriers, and smart responsive surfaces- are designed to address complications including biofilm formation, aseptic loosening, and mechanical wear. This review explores the current state of the literature on innovations in orthopedic implant surface treatments.

METHODS

A literature search was conducted using PubMed, SciSpace, Scopus, and ScienceDirect for studies published in the last 10 years. Articles were selected for relevance to metal hypersensitivity in orthopedic implants, with a focus on diagnostic techniques, clinical outcomes, and innovations in implant coating technologies. Only peer-reviewed original research and systematic reviews in English were included.

RESULTS

After database search and screening, 45 studies were selected for review, including clinical trials, systematic reviews, case reports, and articles discussing diagnostic challenges and techniques in novel coating technologies.

Recent literature increasingly questions the clinical association between metal hypersensitivity and implant failure, particularly in joint arthroplasty. Evidence remains inconclusive and contradictory over concerns of metal allergy. Several reviews and studies have found no consistent association between allergy markers and postoperative complications (Cazzato et al. 2019). For instance, Matar et al.'s scoping review concluded that metal allergy is rare in total knee arthroplasty (TKA) and emphasized informed consent and shared decision-making over routine screening or the use of hypoallergenic implants (Matar et al. 2021). Other authors, including Johnson et al., Frisch et al., and Kotecki et al., have highlighted the lack of reliable diagnostic tools, inconsistent test results, and the absence of validated criteria, collectively casting doubt on the utility of preoperative allergy testing (Kotecki et al. 2023; Johnson et al. 2022; Frisch et al. 2017). As such, implant failure secondary to metal hypersensitivity continues to be a diagnosis of exclusion.

Clinical studies reinforce these findings. Randomized controlled trials and cohort studies have shown that a metal hypersensitivity diagnosis does not significantly affect functional outcomes or complication rates in total joint arthroplasty (TJA), even among patients with documented sensitivities. For example, Postler et al. and Schmidt et al. reported no meaningful differences in outcomes between patients receiving standard versus coated implants. Similarly, studies by DeBenedetti et al., Bravo et al., and Gaillard-Campbell et al. found no correlation between positive allergy tests and adverse outcomes (Gaillard-Campbell and Gross 2024; DeBenedetti et al. 2024; Bravo et al. 2016). These findings support the prevailing view that so-called metal hypersensitivity is unlikely to drive implant failure or persistent pain, and routine metal allergy screening is not supported for the general patient population (Teo and Schalock 2017; Mercuri et al. 2019). Thus, the focus of literature has shifted to understanding the biological interface and emerging advances in surface coating technologies.

ADVANCES IN ORTHOPEDIC IMPLANT COATING TECHNOLOGIES

Innovations in implant coating technologies are emerging to resolve long-standing challenges like infection control, biocompatibility, and tissue integration. Advances in surface coatings and materials science (addressing biocompatibility, mechanical strength, and diagnostic limitations) obviate the clinical relevance of metal hypersensitivity, as the next generation of medical implants show promise in preclinical and clinical settings (Losic 2021; Xu et al. 2022). We will also discuss potential obstacles to clinical adoption of each of these emerging technologies.

SCHOOLS OF THOUGHT IN ANTI-INFECTION COATING DEVELOPMENT

In general, there are two primary schools of thought on coating development in orthopedic implants: biological and chemical. Biology-targeting implants aim to address implant infection by creating a bactericidal surface through conventional antibiotic and antimicrobial modification (i.e., cephalosporin modification). While relatively nontoxic, these biology-targeting coatings would place selective pressure on biofilm-forming bacteria and accelerate the rate of antibiotic resistance over time. The development of bacterial resistance and the maintenance of coating bioactivity after implantation remain the greatest obstacles to the development of biology-based implant coatings. Chemistry-targeting implants aim to address implant infection by preventing bacterial colonization through chemical modifications. These modifications interfere with the bacterial chemistry that facilitates colonization and biofilm formation (i.e., carbon nanotube surface coatings disrupting biofilm chemistry). While this method allows for greater coating stability and modularity, most of these coatings use novel chemistry without previously established toxicity profiles. These uncertain toxicity profiles represent the largest obstacle to clinical adoption of chemistry-targeting implant coatings. Overall, neither school of thought has proven to be superior to the other. Many examples of biology and chemistry targeting implants have also shown improved osseointegration. As a result, many hybrid coating platforms have been developed and studied to utilize the benefits of both modalities.

While other novel approaches, such as induction-heating implants, are under investigation for biofilm management, these remain outside the scope of the present review, which focuses on surface coating technologies.

In this review, we will examine promising examples of emerging coating technologies and manufacturing techniques in each of these categories and discuss future directions to guide further research.

BIOLOGY-TARGETING

ANTIBACTERIAL AND ANTIMICROBIAL COATINGS

Anti-microbial and biofilm resistant materials are at the forefront of research in the area of orthopedic implant coatings. Despite advances in aseptic techniques, implant infection remains one of the top causes of implant failure. These novel coatings aim to address infection rates and act as another barrier of protection against bacterial colonization of implants and biofilm formation. Unfortunately, cost and scalability of manufacturing remain the largest obstacles to wider clinical adoption of these novel coatings. Many of these coatings will also require long term toxicity studies to establish safety profiles for future clinical adoption. This process will require time and as such, renders these options infeasible in the short term. Despite these obstacles, these coatings could radically change the future of orthopedic implant technology and warrant further attention and study.

DBG21 (DeBogy Molecular Inc.): In a preclinical study (Bouloussa et al. 2024), treatment of titanium implants with a proprietary compound called DBG21 produced significant reductions in MRSA biofilm formation compared to untreated implants, without systemic or local toxicity. However, DBG21 treatment is not yet approved for clinical application. Biofilm reduction was as high as 99.97% on implants at Day 7 and similarly significant in surrounding tissues, highlighting a powerful antibacterial effect on the implant surfaces as well as adjacent tissues. The antibacterial compound was applied in a way that it did not release into the body; instead, it was covalently bound to the titanium implant surface (i.e., noneluting). This non-eluting design helps maintain a lasting antibacterial surface without the need for antibiotics that might lead to microbial resistance complications. The significant reduction in MRSA biofilm formation over 14 days (longer than many previously reported rodent studies for implant-related infections), combined with the lack of toxicity, underlines the potential clinical application of these implants in orthopedic and other biomedical fields. Despite promising signs of biofilm reduction, DBG21 has yet to be proven in high stress environments. Most orthopedic implants used in a trauma setting require high tensile strength, while implants used in total joint arthroplasties require high shear force resistance to prevent excessive wear. The DBG21 coating discussed in this study was not examined under high force loads. Polymer coatings are notorious for poor wear resistance but remain popular as a medium for developing novel coatings due to their chemical modularity. **Barrier summary:** Promising antibacterial efficacy in its preclinical stage, but durability testing gaps, manufacturing scalability, and uncertain regulatory trajectory limit clinical adoption.

Silver-based Antimicrobial coatings (aap Implantate and HyProtect): Human clinical trials are underway for an antimicrobial silver coating that's effective against methicillin-resistant Staphylococcus aureus (MRSA). The platform technology is intended for use in trauma and other orthopedic applications. Meanwhile, the German firm BioGate AG's HyProtect antimicrobial coating contains an ultra-thin layer of polysiloxane and silver, which kills multidrug-resistant microorganisms on the surfaces of orthopedic implants (pending FDA review) (van Hoogstraten et al. 2024). Unfortunately, there is concern over the systemic effects of silver-coated implant exposure. Some studies have shown a potentially negative effect on osteoblast differentiation and mineralization (Kontakis et al. 2025). While systemic absorption of large amounts of silver is known to be toxic, multiple studies have shown that serum silver concentration in patients with silver-coated implants remains well below toxic levels (Shivaram et al. 2017; Volker 2017). Despite nontoxic serum silver levels, there are reported cases of surgical site argyria (blue-gray skin pigmentation) in patients who received silver-coated titanium implants (Glehr et al. 2013; Volker 2017). This could be an indication of local silver absorption. Future literature should address the clinical significance of this local absorption and the potentially deleterious effects of silver nanoparticles on postoperative healing and implant wear. **Barrier summary:** A feasible short-term option with ongoing human data (early clinical trials), but long-term durability, local absorption, and the cost of silver deposition remain hurdles.

Antibiotic Peptide Surface Tethering: These coatings are designed to prevent bacterial colonization and biofilm formation on implant surfaces by chemically tethering antibiotics and antimicrobial chemicals to composite surfaces. They have shown efficacy in reducing infection risks in vitro and in vivo studies, although clinical translation remains limited (Fearing et al. 2022). A novel antibiofilm coating based on 5-(4-bromophenyl)-N-cyclopentyl-1-octyl-1H-imidazol-2-amine has shown significant potential. This coating reduces biofilm cells by 1 log in vitro and enhances the effectiveness of antibiotics like cefuroxime without compromising healing or osseointegration in vivo (Coppola et al. 2021). Like most biology-targeting implants, the principal concern of this technology is that it would place selective pressure on common implant-infecting microbes and create antibiotic resistant strains at rapidly increasing rates.

CHEMISTRY-TARGETING

Hydrophobic and Hydrophilic Surface Modifications: Altering implant surface properties can influence bacterial adhesion and biofilm formation. These modifications have demonstrated potential in reducing infection rates by creating surfaces that are less conducive to bacterial growth (Fearing et al. 2022; "Orthopaedic Implant Coatings: Recent Approaches and Clinical Translation" 2022). These chemical modifications will require further study as they

may also affect osseointegration and cell adherence in the bone-implant interface.

CERAMIC COATINGS

Ceramics are renowned for their wear and heat resistance across multiple industrial sectors. These are invaluable characteristics in the high-friction environment of weight-bearing joints. This hardness is unfortunately coupled with poor resistance to shear forces and general inelasticity. Elasticity is measured in a material's elastic modulus (sometimes referred to as Young's modulus). A higher elastic modulus generally implies a non-elastic material. The elastic modulus is a vital consideration in the development of materials for orthopedic implants. Inelasticity results in bone offloading and drastically increases the force gradient across the bone-implant interface. The offloading of bone results in a downregulation of bone remodeling as described in Wolff's Law, leading to poor osseointegration. This phenomenon is known as stress shielding. These conditions often culminate in delamination at the interface and implant failure, resulting in a characteristic "halo sign" on post-operative follow-up x-rays. It is because of these considerations that titanium is the most commonly used metal for orthopedic implants. Titanium, amongst its other material benefits such as resistance to corrosion and wear, has the closest elastic modulus value to natural bone and provides the least risk of stress shielding. Overall, ceramics have much higher elastic moduli and provide a trade off between increased wear resistance and loss of elasticity.

- **TiO_2 and Al_2O_3 Coatings**: These oxide ceramic coatings enhance the surface properties of metallic implants, improving corrosion resistance, wear resistance, and antibacterial properties. TiO_2 coatings, in particular, have shown potential in promoting osseointegration, although long-term clinical data are limited (Wang 2023).
- **Composite Coatings**: Combining different materials to harness synergistic effects is being explored to improve the durability and functionality of coatings. These composite coatings aim to address issues such as coating stresses and thickness uniformity (Wang 2023). Carbon nanotube/hydroxyapatite composites are one such example that has shown promise in previous studies (Nguyen et al. 2020). The synergistic effects of hydroxyapatite's biocompatibility and the antibiofilm properties of carbon nanotubes make it a promising option for coating orthopedic implants (Facca et al. 2011). Like most chemical-targeting implant coatings, carbon nanotubes will require thorough toxicity testing before clinical adoption.

SMART COATINGS

- **Stimuli-Responsive Coatings**: Smart coatings that respond to environmental cues such as temperature, pH, and light are being developed to enhance the interaction between the implant and surrounding tissues. These coatings can provide controlled drug delivery and antimicrobial elution, offering a dynamic response to changing conditions in the body (Joshi et al. 2023). A dual-functional smart polymer foil coating has been designed to address both septic and aseptic failures. It features mechano-bactericidal nanostructures that physically kill pathogens and strain gauges that map implant biomechanics, aiding in early diagnosis and reducing failure risks (Zhang et al. 2023). The material cost of these adaptable coatings currently outweighs their potential clinical utility, but further research into their efficient manufacture is warranted. **Barrier summary:** Strong proof-of-concept in its preclinical stage, but near-term adoption is hindered by cost, scalability, and long-term durability concerns.

WEAR-RESISTANT COATINGS

OXINIUM DIAMOND

The clinical evidence supporting the use of oxinium diamond in orthopedic implants is primarily focused on the material's superior wear resistance, biocompatibility, and potential to enhance osseointegration. Oxinium, a zirconium alloy with a hard ceramic surface, is noted for its effectiveness as a load-bearing surface in joint arthroplasty, particularly for patients with metal hypersensitivity (Roy, Bennett, and Pruitt 2024). However, there are reports of complications such as metallosis due to unintended wear, which can lead to implant failure (Frye, Laughery, and Klein 2021). The use of diamond coatings, including amorphous and polycrystalline diamond, has been explored to address these issues by improving wear resistance, reducing friction, and enhancing the integration of implants with bone tissue (Fong et al. 2021; Zalieckas et al. 2022). Coatings made from biocompatible materials like titanium, hydroxyapatite, and zirconium are being explored to enhance osseointegration and reduce bacterial colonization. These materials improve the implant's interaction with bone tissue and reduce the risk of aseptic loosening (Alontseva et al. 2023; Bohara and Suthakorn 2022). Wear-resistant coatings, such as titanium nitride (TiN) and zirconium nitride (ZrN), have been developed to reduce wear and ion release from implants. These coatings improve implant durability and are particularly beneficial for patients with excessive implant wear or failure (Skjöldebrand et al. 2022). **Barrier summary:** Oxinium (commercially available) is proven but not failure-proof; diamond coatings (preclinical) require cost-effective, reproducible deposition techniques before clinical translation.

ADVANCED MANUFACTURING TECHNIQUES

There are a myriad proposed future coating techniques in medical and industrial applications that could revolutionize the future of orthopedic implant coating manufacturing. The largest obstacles to clinical utility of these methods are cost and scalability. Thermal plasma spraying (TPS) remains the only FDA approved and commercially viable option for manufacturing orthopedic implant coatings. While

effective and scalable, TPS has drawbacks inherent to its design that many of these new techniques aim to address.

- **Thermal Plasma Spraying (TPS)**: TPS allows for the production of tailored porous implants with uniform surface coatings. The process enables control over coating properties, enhancing biocompatibility and osseointegration (Alontseva et al. 2023). Unfortunately, TPS has drawbacks. The high temperatures achieved in plasma sprayed coatings (between 6000 - 16000°C) create cytotoxic byproducts such as calcium oxide (Heimann 2016; Ganvir et al. 2021). Plasma spray also creates an uneven and thick coating on implant surfaces (Ganvir et al. 2021). Thicker coatings experience greater shear forces at the bone/implant interface, which often results in delamination. Many studies have shown that coating thicknesses less than 20 micrometers are desirable, as they minimize shear forces and preserve more of the surface area within the microarchitecture of the metal surface (Heimann 2016). **Barrier summary:** Scalability is established for TPS but limited by durability issues; newer approaches must prove reproducibility and cost efficiency.
- **High Velocity Suspension Flame Spraying (HVSFS)**: This experimental method is used to apply calcium alkali orthophosphate coatings, which have shown potential in enhancing osseointegration due to their bioactivity and resorbability. These coatings promote better cell penetration and stability at the implant-bone interface. The high temperatures and high variability in nanoparticles in this method predispose it to the same pitfalls as thermal plasma spraying (Lanzino et al. 2024).

While these advancements represent significant progress in coating technologies for orthopedic implants, their clinical translation is limited, with few commercially available products. Long-term clinical data are sparse, particularly for newer materials and techniques. Additionally, issues such as coating durability, stress, and uniformity need to be addressed to ensure the reliability and effectiveness of these coatings in real-world applications ("Orthopaedic Implant Coatings: Recent Approaches and Clinical Translation" 2022; Mosas et al. 2022).

DISCUSSION

Contemporary research in orthopedic implant technology views metal hypersensitivity as an obsolete clinical concern and instead focuses on advances in surface coatings to enhance the biological interface between implants and host tissue. Technologies such as antimicrobial coatings, ceramic barriers, and smart, responsive surfaces are being developed to mitigate complications such as biofilm formation, aseptic loosening, and mechanical wear.

Postoperative infection remains one of the most costly and debilitating complications in arthroplasty. In response, several groups have explored implant surfaces that actively resist bacterial colonization. Notably, a titanium surface treated with DBG21 , a proprietary material, demonstrated a dramatic 99.97% reduction in *Staphylococcus aureus* biofilm formation in vivo, without systemic toxicity or adverse local tissue effects. Unlike traditional eluting coatings, DBG21 is covalently bonded to the implant, offering durable antimicrobial protection. Silver remains a cornerstone in antimicrobial surface design. Bio-Gate AG's HyProtect® coating, which incorporates silver into a polysiloxane matrix, is under FDA review and designed to address multidrug-resistant organisms. Similarly, aap Implantate's antimicrobial silver-coated trauma hardware has entered human trials. While promising, long-term clinical data for these coatings are still limited.

Beyond metallic agents, surface-tethered antimicrobials and peptides have shown efficacy in preclinical models. A novel imidazole-based coating reduced biofilm burden and improved the efficacy of systemic antibiotics in vivo, without compromising osseointegration. However, the issue of accelerating bacterial resistance in the setting of these biology-targeting implant coatings remains. Other strategies, such as modifying implant surface hydrophobicity or hydrophilicity, may reduce microbial adhesion. Oxide ceramics continue to be explored for their potential to reduce corrosion, support bone apposition, and minimize wear-related inflammation. Composite coatings, particularly carbon nanotube–hydroxyapatite coatings, have drawn attention for combining osseointegrative properties with antibiofilm effects. These hybrid materials may address the historical tradeoff between mechanical durability and bioactivity, but their toxicity profiles are yet to be established.

"Smart coatings" are being developed to release drugs or change surface characteristics in response to environmental cues, such as infection, pH shifts, or mechanical stress, potentially aiding early diagnosis of implant loosening. Coatings composed of titanium, zirconium, and hydroxyapatite are favored for their ability to reduce fibrous encapsulation, promote bone bonding, mitigate ion release, and extend implant lifespan.

The manufacturing techniques for these novel coatings have proven just as important as the coatings themselves. Additive manufacturing has enabled precise control over coating thickness, pore size, and roughness. These microstructural details can significantly affect bone ingrowth and implant stability. Still, techniques such as thermal plasma spraying present significant drawbacks, due to the extreme heat involved and cytotoxic byproducts. High-velocity suspension flame spraying (HVSFS) offers improved coating uniformity, enhancing cell adhesion and interface stability, though variability in nanoparticle content and heat-related challenges hinder clinical translation.

Oxidized zirconium (Oxinium) is commercially available and widely adopted for its wear resistance, though metallosis and premature failure can still occur if the ceramic surface is compromised. Both amorphous and polycrystalline diamond layers have demonstrated friction-reducing and biocompatible properties in preclinical settings, though large-scale orthopedic trials are lacking.

In summary, advances in materials science have driven meaningful progress in orthopedic implant technology, though clinical adoption has been slow. Key obstacles include scalability, regulatory hurdles, and a scarcity of long-term clinical outcome data. Thus, technologies may be considered along a spectrum of readiness (at the time of writing this review):

- **Preclinical:** DBG21, diamond coatings, smart coatings
- **Early Clinical Trials:** HyProtect®, aap Implantate silver coatings
- **Commercially Available:** Oxinium, titanium nitride coatings, thermal plasma spraying

The most promising for near-term clinical adoption are:

1. Silver-based antimicrobial coatings (HyProtect®, aap Implantate)
2. Hybrid ceramic–antimicrobial coatings
3. Titanium nitride wear-resistant coatings

These candidates benefit from advancing clinical trial data, prior regulatory familiarity, and demonstrated mechanical durability.

Translational barriers include:

- **Cost:** High manufacturing and material costs (particularly for smart and diamond coatings)
- **Durability:** Limited long-term performance data in load-bearing conditions
- **Reproducibility:** Manufacturing variability, especially in additive methods
- **Regulatory hurdles:** Uncertainty for newer nanomaterials

By framing innovations by maturity stage and barriers, this review highlights that hybrid coatings, which combine antibacterial and osseointegrative properties, may represent the optimal balance between clinical feasibility and long-term impact.

Future research must bridge the gap between promising materials science and reproducible, patient-centered outcomes while also addressing the toxicity profiles of the myriad coating materials under development. In the short term, biology-targeting implants may represent the next stage of implant development. Ultimately, the technology would require the marriage of two well-established, tested technologies: antibiotics and medical metallurgy. The obstacles to clinical adoption, such as toxicity profiles, efficacy against bacteria, and mass production, have already been overcome by commonly used antibiotics and titanium implants. This next phase of orthopedic implant manufacturing may bridge the gap to future advancements in medical metallurgy and chemical modification, as this review notes. Biology-targeting implants may have short-term potential, but their risk of accelerating bacterial resistance may hinder their long-term adoption. As a result, it appears that hybrid coatings that utilize the benefits of both approaches might offer the optimal balance between preventing bacterial resistance and bactericidal activity.

CONCLUSIONS

Orthopedic implant technology is advancing through the development of evidence-based surface treatments that directly address real clinical challenges such as infection, poor integration, and material degradation. Recent breakthroughs in coating technologies for orthopedic implants have the potential to significantly improve patient outcomes by reducing infection rates, enhancing biocompatibility, and improving mechanical properties.

Novel biology-targeting, chemistry-targeting, and hybrid implant coatings offer the potential to enhance implant longevity and reduce complications. Future success will depend on validating these technologies through long-term clinical data and overcoming barriers to widespread implementation. Addressing these gaps will be crucial for combating implant infection and ensuring the best outcomes for patients receiving orthopedic implants.

While the initial goal of the studies is to establish proof of concept and efficacy, the cost of manufacturing remains a deciding factor in the future clinical adoption of novel technologies. Future research should include cost analyses of new materials and methods to assess the feasibility of new technologies after efficacy has been established.

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