

Review Article

Surface coating with pharmacological molecules

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ABSTRACT

The application of pharmacological molecules in surface coatings has emerged as an innovative approach to enhance the effectiveness and safety of surgical procedures. This review outlines the concept and potential uses of pharmacologically coated surfaces in surgical settings. By applying a thin layer of bioactive compounds to surgical implants or devices, these coatings provide a comprehensive strategy to tackle issues such as infection control, implant integration and tissue regeneration. Various techniques, including physical and chemical vapour deposition as well as electrospinning, can be utilised to achieve precise management of drug release rates and coating durability. In fields such as orthopaedics, cardiovascular surgery and plastic surgery, pharmacologically coated surfaces show significant promise in enhancing biocompatibility, minimising infection risks and facilitating tissue healing. However, the use of pharmacological coatings also presents several challenges and considerations. It is crucial to ensure the long-term stability and effectiveness of these coatings, as variations in drug release rates may affect therapeutic results. In addition, compatibility with current surgical materials and methods must be assessed to guarantee smooth integration into clinical practice. Addressing issues such as long-term stability, material compatibility, and regulatory requirements is essential for the successful implementation of this technology in clinical settings.

Keywords: Coating, Drugs, Pharmacodynamics, Pharmacology, Surfaces

INTRODUCTION

In the continuously changing realm of surgical practice, the quest for novel techniques and technologies is essential for enhancing patient outcomes and progressing the discipline.^[1] The application of pharmacological molecules as surface coatings signifies a promising advancement in surgical innovation, with the potential to improve the safety, effectiveness and adaptability of surgical techniques.^[2] This method seeks to tackle persistent issues such as infection, integration of implants and tissue regeneration by coating surgical implants and devices with a thin layer of bioactive materials.^[3]

The application of pharmacological molecules as surface coatings presents an innovative strategy to tackle these issues, utilising the therapeutic benefits of drugs and biologics to enhance patient outcomes.^[4] Historically, surgical procedures have faced challenges due to complications including implant rejection, bacterial infections and inadequate healing.^[5] The incorporation of pharmacologically active substances into surface coatings offers an innovative approach to address these challenges. By utilising the therapeutic effects of drugs and biologics,

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surfaces that are pharmacologically coated can influence biological reactions at the interface between the implant and surrounding tissue, thereby enhancing beneficial results and reducing negative effects.^[6]

This review establishes a foundation for an in-depth examination of the use of pharmacological molecules in surface coatings within the field of surgery. We will investigate the development, applications, advantages, challenges and future potential of this cutting-edge technique. By fostering interdisciplinary collaboration and advancing scientific knowledge, the application of pharmacological surface coatings has the potential to revolutionise surgical practices, paving the way for a new era of precision medicine and enhanced patient outcomes.

PRINCIPLES OF SURFACE COATING

Surface coating, often referred to as surface finishing, entails the application of a protective or aesthetic layer onto the surface of a substrate. The fundamental principles of surface coating encompass several elements, such as the choice of coating materials, techniques for application, curing procedures and measures for quality assurance.^[7] Here are some fundamental principles:

- **Substrate Preparation:** The effective preparation of the substrate is essential for ensuring strong adhesion and long-lasting durability of the coating. This process may include steps such as cleaning, degreasing, sanding and, in some cases, the application of a primer or conversion coating to improve adhesion.^[8,9]
- **Selection of Coating Material:** Selecting the appropriate coating material is influenced by several factors, including the type of substrate, environmental conditions and the specific aesthetic and performance criteria needed, such as resistance to corrosion, chemicals and ultraviolet (UV) light.^[10]
- **Application Method:** Different techniques exist for the application of coatings, such as spraying, brushing, dipping, rolling, electroplating and powder coating. The selection of a particular method is influenced by several factors, including the nature of the coating, the geometry of the substrate, the volume of production and the quality of finish required.^[11,12]
- **Curing or Drying:** Following application, the coating is required to undergo a curing or drying phase to establish a solid, adherent layer. Curing techniques may encompass air drying, heat curing (such as microwave curing)^[13] and chemical curing (e.g. crosslinking)^[14] or UV curing.^[15]
- **Quality Control:** Quality control measures are crucial for verifying that coated products fulfil established criteria. This process involves examining substrate characteristics, including integrity, uniformity, surface roughness, thickness and hydrophilicity.^[16]

- **Environmental and Safety Considerations:** Surface coating procedures frequently utilise chemicals, which can lead to the production of hazardous waste or emissions. Consequently, it is essential to establish appropriate safety protocols and environmental regulations to reduce health risks for workers and mitigate environmental effects.^[17]

APPLICATIONS IN SURGERY

In the field of surgery, surface coating involves the application of various coatings or surface treatments to medical devices, implants or surgical instruments with the aim of improving their performance, biocompatibility and safety. The underlying principles of surface coating in this context are centred on enhancing the functionality and biocompatibility of these devices, ultimately leading to improved outcomes for patients.^[2,18,19] Initially, it is essential for surface coatings to possess biocompatibility, which indicates that they do not provoke detrimental responses on interaction with biological tissues. Coatings that are biocompatible contribute to the reduction of tissue irritation, inflammation and the likelihood of negative reactions, thereby enhancing the safety of medical devices intended for use within the human body.^[20] Coatings can be utilised on surgical instruments or implants to minimise friction and wear throughout surgical operations. The application of low-friction coatings enhances the manoeuvrability of instruments and decreases tissue damage, resulting in improved surgical results and expedited recovery for patients.^[21,22] In addition, certain surface coatings include antimicrobial substances designed to inhibit bacterial growth and diminish the likelihood of surgical site infections. Such coatings contribute to preserving a sterile surgical environment and decreasing the occurrence of postoperative complications.^[23,24] In addition, coatings that possess lubricating characteristics can be utilised on surgical instruments or devices to promote seamless movement and decrease friction throughout procedures. Improved lubrication can enhance the effectiveness of surgical operations and lessen the risk of tissue injury.^[25] Surface coatings can exhibit anti-adhesive characteristics that inhibit the attachment of biological substances, including blood, tissue and other bodily fluids. These anti-adhesive properties are beneficial in surgical settings, as they enhance visibility and simplify the cleaning and sterilisation processes of surgical instruments.^[26,27] Coatings play a crucial role in safeguarding surgical instruments and implants against corrosion, which may arise from contact with bodily fluids or aggressive chemical conditions within the body. By utilising corrosion-resistant coatings, the durability of medical devices is enhanced, thereby ensuring their effective performance over an extended period.^[28,29] Surface coatings can be customised to alter particular surface characteristics of medical devices, including hydrophobicity.^[30] Finally, the

surface coatings used on medical devices are required to adhere to regulatory standards and requirements to guarantee their safety and effectiveness. Regulatory organisations, including the U.S. Food and Drug Administration and the European Medicines Agency, establish guidelines for the assessment and authorisation of coatings for medical devices.^[31] A summary is shown in Table 1.

PHARMACOLOGICALLY COATED SURFACES

Pharmacologically coated surfaces provide numerous advantages across a range of medical applications, especially within the domains of interventional orthopaedics, dentistry and cardiology.^[32,33] Pharmacologically coated surfaces have the capability to locally deliver antiplatelet or anticoagulant drugs, thereby aiding in the prevention of thrombosis, or blood clot formation, on medical devices such as stents and catheters. This function is especially vital in interventions such as coronary angioplasty and stent insertion, as thrombosis can result in severe complications, including heart attacks or strokes.^[34,35]

Restenosis, characterised by the re-narrowing of the artery, may arise in coronary stents as a result of excessive tissue proliferation at the stent implantation site. The application of pharmacological agents to the surfaces of medical devices can improve their biocompatibility, thereby minimising the likelihood of negative reactions or inflammatory responses. This consideration is especially crucial for long-term implants, such as vascular stents and orthopaedic devices.^[35] Pharmacologically coated surfaces facilitate the precise and localised administration of drugs to designated target areas within the body. This method of targeted drug delivery reduces systemic side effects while enhancing therapeutic effectiveness by directing medications straight to the intended site of action.^[36-38] Applying pharmacological agents that stimulate bone growth or reduce inflammation to orthopaedic implants can facilitate the healing process and enhance the integration of the implant with adjacent tissues. This approach may result in quicker recovery periods and better long-term results for patients undergoing joint replacement procedures.^[39] Certain surfaces treated with pharmacological coatings include antimicrobial substances

Table 1: Main medical surface coating applications.

Topic	Key points	Applications
Surface coatings in surgery	Improve biocompatibility, functionality and safety	Reduce friction, wear and tissue trauma
	Biocompatibility: minimises adverse reactions	Prevent bacterial infections (antimicrobial agents)
	Low-friction and lubricating coatings for smoother operations	Enhance recovery times, prevent adhesion of biological materials and protect against corrosion
	Regulatory compliance (Food and Drug Administration, European Medicines Agency) is essential for safety and efficacy	Increase surgical instrument longevity and improve patient outcomes
Pharmacologically coated surfaces	Release drugs (e.g. antiplatelet, anticoagulants) to prevent thrombosis and restenosis.	Used in orthopaedics, cardiology and dentistry
	Localised drug delivery, minimising systemic side effects	Promote bone growth in implants and prevent infections
	Enhance device biocompatibility, reducing inflammation	Improve long-term outcomes of medical devices such as stents and implants
Anticorrosion coatings	Coatings on metallic materials (e.g. titanium and magnesium) protect from corrosion	Applied to stents, implants, dental devices and orthopaedic fixations
	Graphene oxide and PEDOT coatings are effective corrosion barriers	Prevent corrosion in magnesium and titanium implants
	Can be synthesised directly on metallic substrates	Enhance lifespan and performance of biomedical devices
Antibacterial coatings	Contact-active antimicrobial coatings kill pathogens without releasing agents	Applied to surgical instruments and medical devices to prevent infections
	Eco-friendly, utilises antimicrobial polymers (e.g. chitosan, antimicrobial peptides and polyaniline)	Enhance sterilisation and minimise microbial growth on medical devices
	Can be designed for slow, continuous or triggered release of antimicrobial agents	Combat bacterial resistance and improve clinical outcomes in healthcare settings
	Challenges include high fabrication costs and possible depletion of biocides over time	Commonly used on smaller objects, with some promising results on larger surfaces

PEDOT: Poly(3,4-ethylene dioxythiophene)

that aid in inhibiting bacterial growth and minimising the likelihood of infections related to implants. This is especially crucial for devices like urinary catheters, as infections can result in significant complications.^[40] Pharmacologically coated surfaces can extend the longevity of medical devices and minimise the necessity for additional procedures or device replacements by mitigating complications such as thrombosis, restenosis and infection.^[41] Pharmacologically coated surfaces enable the personalisation of treatment according to the unique requirements of each patient. Various medications or drug combinations can be integrated into these coatings to target diverse medical conditions or specific patient attributes.^[42] Pharmacologically coated surfaces present considerable opportunities to enhance the safety, effectiveness and durability of medical devices and implants, ultimately resulting in improved clinical results and superior patient care. A summary is shown in Table 1.

ANTICORROSION COATINGS

Metallic materials find a wide range of applications in the fields of medicine and dentistry, including dental implants, orthopaedic fixations, orthodontic devices, joint replacements, stents, as well as endodontic files and reamers.^[43] The drawback associated with these biomaterials is the release of metal ions, including nickel, titanium and silver (Ag). Consequently, the application of coatings on metallic materials is crucial in addressing these issues.^[43,44] Although numerous coatings are currently being explored for application on metallic biomaterials, particularly nitinol, achieving a successful coating remains a persistent challenge.^[45-58] Significant drawbacks associated with polymer coatings encompass the toxicity linked to the roughness of the components, their porosity and the potential for the coatings to detach.^[59] Graphene, despite being only one atom in thickness, exhibits inert properties and demonstrates resistance to both water and oxygen. The combination of these properties, along with their durability and atomic stability, has demonstrated that graphene is effective as a corrosion barrier film.^[60-63] Magnesium (Mg) has the potential to be utilised in the production of biodegradable implants; nevertheless, its primary limitation lies in the challenges associated with managing its corrosion rate effectively. Catt *et al.*^[61] introduced a conductive polymer, poly(3,4-ethylene dioxythiophene) (PEDOT), in conjunction with a graphene oxide (GO) coating for Mg implants, with the objective of reducing corrosion. Their research revealed a significant decrease in the concentration of Mg ions and a lowering of the pH in the surrounding environment, suggesting improved corrosion resistance. In addition, a decrease in hydrogen gas evolution was noted. The efficacy of the coating can be attributed to three primary factors: The development of a passive layer that restricts solution

infiltration, the presence of negative charges on the film and the formation of a corrosion-resistant Mg-phosphate layer. Moreover, the coating exhibited promising biocompatibility *in vitro*, showing no toxic effects on cultured neuronal cells. As a result, the PEDOT/GO coating is demonstrated to be effective in preventing corrosion in Mg-based implants. Zhou *et al.*^[63] investigated the bioactive characteristics of titanium substrates coated with GO in relation to periodontal ligament stem cells (PDLSCs), comparing these results with those obtained from sodium titanate substrates. The results revealed that PDLSCs grown on GO-coated titanium substrates exhibited a marked increase in alkaline phosphatase (ALP) activity, higher proliferation rates and elevated expression levels of osteogenic genes, including ALP, runt-related transcription factor 2 (Runx2), bone sialoprotein and osteocalcin (OCN), in comparison to those cultured on sodium titanate substrates. In addition, the presence of GO significantly enhanced the protein expressions of Runx2, bone sialoprotein and OCN. Graphene can be directly synthesised on various metallic substrates, including Mg, zinc, nickel and aluminium, leading to the creation of a protective layer.^[60,62,64] Singh *et al.*^[65] effectively created a graphene composite coating designed to inhibit corrosion on copper (Cu) substrates. In the field of dentistry, graphene coatings have the potential to protect a range of metallic biomaterials, including archwires, files, reamers and various types of metallic prostheses, from corrosion. Hikku *et al.*^[66] investigated the anti-corrosion characteristics of a graphene and polyvinyl nanocomposite coating applied to aluminium-2219 alloy. Graphene coatings have the potential to enhance the surface characteristics of implants while simultaneously mitigating corrosion.^[67,68] Suo *et al.*^[67] successfully created a uniform coating composed of GO/chitosan/hydroxyapatite (GO/CS/HA) on titanium substrates using electrophoretic deposition. This innovative GO/CS/HA coating demonstrated enhanced wettability and bonding strength when compared to coatings made solely of HA, GO/HA and CS/HA. In addition, the GO/CS/HA coating significantly enhanced cell-material interactions *in vitro* and promoted osseointegration *in vivo*. As a result, the utilisation of GO/CS/HA coatings on titanium emerges as a promising strategy for applications in implant dentistry. The GO coating holds considerable potential in tissue engineering and regenerative medicine, particularly in areas such as managing root fractures, cementing prosthetic devices, pulp therapy and addressing bone defects through filling, repair and regeneration. These applications may greatly benefit from the use of bioactive cement, which is known for its capacity to release calcium ions (Ca²⁺), increase the alkalinity of the surrounding environment and encourage cell differentiation and the development of mineralised tissue. However, it is crucial to acknowledge that bioactive cement often suffers from insufficient mechanical properties, rendering it vulnerable to fractures due to its limited

strength and fracture toughness.^[69] The incorporation of graphene enhances the mechanical properties significantly. An increase in the strength of 58S bioactive glass was noted, with a doubling effect achieved through the addition of 0.5 wt.%.^[70] The incorporation of GO^[70] and reduced GO (rGO)^[71] has demonstrated notable enhancements in mechanical properties. Specifically, the introduction of rGO at a concentration of 1 wt.% led to a remarkable 200% enhancement in the fracture toughness of HA.^[70] The addition of graphene markedly improves the bioactive properties of bone cement. Studies have shown that different cell types, including bone marrow stem cells, PDLSCs and dental pulp stem cells, demonstrate spontaneous osteogenic differentiation when in contact with pristine graphene scaffolds and substrates created through chemical vapour deposition.^[72,73] *In vivo* bone formation was demonstrated through the implantation of GO-coated collagen scaffolds into the tooth extraction sockets of beagle dogs. After a period of 14 days, the GO-coated scaffolds exhibited enhanced bone formation and calcium absorption, in contrast to the control scaffolds, which were predominantly occupied by connective tissue.^[74] A summary is shown in Table 1.

ANTIBACTERIAL COATINGS

Contact-active antimicrobial coatings (AMCs) are designed to eliminate pathogens through direct contact, without the need for antimicrobial substances to leach from the surface. These coatings can be applied in extremely thin layers, even at the molecular level, which reduces the amount of antimicrobial agents needed, thereby enhancing their potential for environmental sustainability. It is crucial that the active antimicrobial agents are securely bound to the surface and contain functional antimicrobial groups. The biocidal action of these coatings is dependent on their interaction with pathogens and does not involve the release of active agents, allowing for prolonged antimicrobial effectiveness unless the surface is compromised by factors such as the accumulation of dead cells or other contaminants. In general, contact-active coatings are derived from antimicrobial polymers, which can be categorised as either natural – obtained directly from natural sources or synthesised to imitate natural substances – or synthetic, created from chemical monomers. These antimicrobial polymers are affixed to surfaces to create contact-active coatings that retain their antimicrobial efficacy.^[75]

Coatings that utilise CS, a biocompatible polysaccharide made up of N-acetylglucosamine and D-glucosamine, offer a promising avenue for contact-active AMCs. This natural cationic polymer demonstrates antimicrobial efficacy attributed to the positively charged amine groups within its molecular structure. As a sustainable biocide, the antimicrobial effectiveness of CS can be fine-tuned by

modifying the amine functionalities and incorporating them into suitable polymer matrices.^[75] During the biocidal action, the surface of a polycationic biocide may become covered with dead cells, resulting in a loss of antimicrobial activity. However, the activity of these surfaces can be restored through washing with cationic detergents, which help remove the accumulated cellular debris.^[75] An alternative class of antimicrobial substances that can be anchored to surfaces through polymeric brushes is antimicrobial peptides (AMPs).^[76] AMPs, such as magainin and defensin, or their synthetic mimics, can be integrated into contact-active AMCs.^[76-78] The antimicrobial mechanism of AMPs is primarily attributed to two key properties: a highly rigid backbone and the strategic arrangement of one hydrophobic and one cationic side group. These structural features enable the AMP to effectively penetrate and disrupt the cell membrane.^[76-78]

A typical contact-active AMC, such as a quaternary ammonium compound (QAC), forms electrostatic interactions with negatively charged components of the cell membrane, disrupting the integrity and function of the entire cell. At lethal concentrations, QACs can displace cytoplasmic components and dissociate phospholipids.^[79] Direct incorporation of QAC into coatings often results in high levels of leaching, rapid depletion of the biocide and increased environmental toxicity. A more widely accepted approach involves grafting the active QAC onto a polymer, which facilitates binding and anchoring of the QAC to various surfaces.^[80] The biocide 3-(trimethoxysilyl)propyldimethyloctadecyl ammonium chloride, an organosilicon QAC (Si-QAC)^[80,81] is anchored to surfaces through the silane group of the Si-QAC, which condenses with free hydroxyl groups on the surface. This anchorage is further stabilised by intermolecular siloxane (Si-O-Si) linkages.^[82,83] The antimicrobial action of Si-QAC is primarily attributed to the quaternary amine (N⁺) group, which attracts negatively charged microbial cells. These cells are then drawn to the needle-like C18 structure of the hydrophobic chain, leading to puncture of the bacterial cell envelope and subsequent events that result in cell death.

Polyaniline (PANI) has been identified as a promising material for contact-active AMCs.^[84,85] The surface of PANI is conductive, attracting negatively charged bacteria through electrostatic interactions.^[86] However, the antimicrobial activity of PANI can be influenced by changes in its structural chemistry with pH; specifically, the emeraldine salt form exhibits greater activity than the emeraldine base form, which may pose challenges to maintaining sustained antimicrobial efficacy.^[87,88] The commercialisation of contact-active AMCs is fraught with greater difficulties than that of biocide-releasing AMCs, primarily due to the elevated production costs and longer timeframes involved. Although

contact-active AMCs are generally considered to be less harmful to the environment than their biocide-releasing counterparts, the active components within them can still become depleted over time. On the other hand, biocide-releasing AMCs, which follow a more traditional design approach, provide a variety of broad-spectrum agents for controlled release. Nevertheless, they encounter multiple challenges, such as interference from residual dead cells, depletion of the biocide reservoir that restricts the active lifespan of the surface and the risk of developing resistance at sub-minimum inhibitory concentration levels. Furthermore, the release of biocides may introduce potential hazards related to human and environmental toxicity.^[89] Biocide-releasing AMCs can be categorised based on the biocide release mechanism. The simplest form involves continuous release, where a biocide gradient creates an outer inhibition zone and an inner kill zone to protect the surface from pathogen colonisation. While such surfaces can prevent microbial attachment, they deplete quickly and require frequent replacement. Common biocides for these AMCs include metals, metal oxides and nanoparticles of Ag and Cu. Ag, widely recognised for its biocidal activity, works by accumulating positively charged ions at the negatively charged regions of the microbial cell membrane, causing membrane damage and cell death. Ag-based AMCs may incorporate Ag alloys, nanoparticles, Ag oxide, chelated Ag, metallic Ag or Ag salts. Among these, Ag nanoparticles have shown superior efficacy, as they not only release Ag ions but also generate reactive oxygen species, directly damaging the cell membrane. Cu, a cost-effective alternative to Ag, also exhibits strong biocidal properties, including effective DNA degradation that limits the transmission of antibiotic and biocide resistance genes.^[90] While both Ag and Cu coatings show high antibacterial and antiviral activity^[90] their application has been primarily tested on small objects, such as doorknobs and bed rails, with limited testing on large surfaces like walls. Moreover, the real-world effectiveness of these coatings in reducing healthcare-associated infections (HAIs) remains under investigation, although some studies show promising results for Cu coatings. One major limitation of Ag coatings is their reduced efficacy under low temperature and humidity conditions, which often reflect real-world settings. To address the rapid depletion of biocides in continuous release AMCs, slow-release mechanisms have been explored. By incorporating biocides into a polymer matrix, the release rate can be controlled. Techniques such as drug delivery systems can be employed, using biocide carriers such as polylactic acid, polyesters or polyelectrolyte multilayers to enable slow release. In antibiotic-based AMCs, HA is often used as a biocompatible carrier, with modified forms such as carbonated hydroxyapatite offering improved incorporation and slower release of antibiotics. Some AMCs, such as those incorporating Ag without continuous

release, fall under slow-release mechanisms. For example, glass slides coated with nanosilver (1–2 nm) and modified with poly(ethyleneimine) exhibit significant antimicrobial activity against *Escherichia coli* without releasing substantial amounts of Ag into the environment. Slow-release coatings are expected to maintain antimicrobial efficacy for longer periods compared to continuous-release coatings, although their higher cost may limit their use on large objects. Continuous leaching of biocide from AMCs raises concerns about their efficiency and durability. Ideally, surfaces should be capable of detecting microbial presence and releasing biocides only when necessary. Triggered-release biocidal coatings address this issue by responding to specific external stimuli, such as bacterial molecules or host infection signals. For instance, quorum-sensing molecules, such as homoserine lactones in Gram-negative bacteria, can trigger biocide release when their concentration exceeds a threshold value. An example includes the release of ciprofloxacin in response to quorum-sensing lipase-sensitive homoserine groups on a polyethylene glycol-like polymer. Another example involves a thrombin-degradable peptide linker cross-linked with polyvinyl alcohol, which releases encapsulated antibiotics in response to an increase in thrombin during infection. While triggered-release AMCs offer a more sophisticated approach than continuous or slow-release coatings, their complexity may limit their applicability to specialised surfaces. The requirement for specific stimuli to activate the coating raises questions about the specificity and reliability of activation. Alternative approaches have been suggested, including external triggers such as temperature or pH, to indicate infection or colonisation and activate cleaning mechanisms. A summary is shown in Table 1.

LIMITATIONS

While pharmacologically coated surfaces offer numerous benefits, they also come with several challenges and limitations that need to be addressed. Ensuring the biocompatibility and safety of pharmacological agents used in coatings is crucial. Some drugs may elicit allergic cause adverse effects in predisposed individuals. In addition, the long-term effects of exposure to these drugs on surrounding tissues need to be thoroughly evaluated. Achieving the optimal release kinetics of drugs from coated surfaces is challenging. The release rate must be carefully controlled to maintain therapeutic levels at the target site while minimising systemic exposure and potential side effects. Coatings must adhere securely to the underlying substrate and maintain their integrity under physiological conditions. Surface degradation, delamination or premature drug release can compromise the efficacy of the coating and increase the risk of complications such as thrombosis or infection. Pharmacologically coated surfaces must be compatible with the design and materials of medical devices. Manufacturers must demonstrate the safety,

efficacy and consistency of the coating through rigorous preclinical and clinical testing, adding time and cost to the development process. The incorporation of pharmacological agents into coatings can increase the production costs of medical devices. Cost-effectiveness analyses are necessary to justify the added expense and demonstrate the value of pharmacologically coated surfaces compared to conventional treatments or devices. Patient variability in response to pharmacological treatments poses a challenge for pharmacologically coated surfaces. Factors such as genetic variability, comorbidities, efficacy and safety complicate the prediction of clinical outcomes. Addressing these challenges requires interdisciplinary collaboration among researchers, clinicians, engineers and regulatory agencies to develop innovative coating technologies that are safe, effective and commercially viable. Continued research and technological advancements are needed to overcome these limitations and realise the full potential of pharmacologically coated surfaces in improving patient care.

FUTURE DIRECTIONS

The future of pharmacologically coated surfaces holds promise for advancing medical treatments and improving patient outcomes. With advancements in genomics and precision medicine, there is increasing interest in developing pharmacologically coated surfaces tailored to individual patient profiles. Customised coatings could deliver specific drugs or combinations of drugs based on genetic markers, biomarkers or patient characteristics, optimising treatment outcomes and minimising side effects. Nanotechnology offers opportunities to engineer coatings with precise control over drug release kinetics, surface properties and targeting capabilities. Nanoparticles, nanofibers and nanostructured surfaces can enhance the efficacy and stability of pharmacological agents, enabling more efficient drug delivery and tissue integration. Bioactive coatings that promote tissue regeneration, angiogenesis or antimicrobial activity are gaining traction for various medical applications. Incorporating growth factors into coatings can stimulate healing and improve the biocompatibility of medical devices, particularly in orthopaedics and tissue engineering. Smart coatings equipped with sensors, stimuli-responsive materials or feedback mechanisms have the potential to revolutionise drug delivery and monitoring in real-time. Bioresorbable coatings that degrade over time and are absorbed by the body offer advantages in reducing long-term implant-related complications and eliminating the need for device removal surgeries. These coatings can be designed to deliver drugs during the critical early stages of healing before being safely metabolised and eliminated. Coatings designed to modulate the immune response, such as anti-inflammatory or immunomodulatory agents, hold potential for improving

the biocompatibility and longevity of medical implants. Immune-modulating coatings could mitigate chronic inflammation, fibrosis or rejection reactions, enhancing tissue integration and device performance. Integrating regenerative medicine principles into coatings aims to create biomimetic environments that support tissue regeneration and repair. Coatings mimicking the extracellular matrix, bioactive peptides or growth factors can guide cell behaviour and promote tissue-specific regeneration, offering new solutions for regenerative therapies and organ transplantation. These future directions in pharmacologically coated surfaces reflect the ongoing efforts to develop innovative technologies that address unmet medical needs, enhance therapeutic outcomes and advance the field of medical device coatings. Collaboration among researchers, clinicians, industry partners and regulatory agencies will be essential to translate these advancements from the laboratory to clinical practice effectively.

METHODOLOGY

We performed a comprehensive search in databases such as PubMed, Scopus, Web of Science and Google Scholar, using search terms related to the interaction between pharmacologically coated surfaces, microbial activity and host immune responses (i.e. AMCs, immune response to coated biomaterials, pharmacological surface modification and infection control, bioactive coatings and host response, drug-eluting surfaces and immune modulation). We included studies involving both *in vitro* and *in vivo* models to gather insights into the mechanisms of interaction. Experimental research, clinical trials, case studies, qualitative analyses and review articles were included to provide a comprehensive perspective, with a particular focus on the role of coated surfaces in modulating immune responses and preventing microbial colonisation in biomedical and clinical contexts.

Research strategy

We performed a comprehensive search in databases such as PubMed, Scopus, Web of Science and Google Scholar, using search terms related to the interaction between pharmacologically coated surfaces, microbial colonisation and immune system responses (i.e. drug-eluting surfaces and microbiota, AMCs immune response, bioactive coatings and host interaction, surface modification infection control and immune modulation by coated biomaterials). We included studies exploring both *in vitro* and *in vivo* models to gather insights into the underlying interaction mechanisms. Qualitative studies, experimental research, clinical trials, case studies and review articles were included to provide a complete perspective, prioritising studies that investigated the relationship between pharmacologically active surface

coatings and their impact on microbial behaviour and immune system modulation in biomedical applications.

Eligibility criteria

Human studies (clinical trials, observational studies and cohort studies) focused on the interaction between pharmacologically coated surfaces and microbial behaviour or immune responses were considered eligible, as were animal studies or microbiome-related studies that provide insight into the immune modulation by pharmacologically active coatings. Studies investigating the role of pharmacologically coated surfaces in modulating immune responses (both innate and adaptive immunity) and alterations in microbial colonisation were included in the study. Research examining the effect of pharmacological coatings on microbial dysbiosis and how these coatings influence the progression of infection or immune modulation was also considered eligible. Studies that do not specifically address the interaction between pharmacologically coated surfaces, microbial dynamics and immune system modulation were excluded from the study.

Data extraction

Data were extracted by considering the type of pharmacologically coated surfaces analysed (e.g. AMCs, drug-eluting coatings and bioactive coatings), as well as the specific properties of these surfaces (e.g. type of drug released, coating material and surface topography) and the methods used to evaluate their effects (e.g. surface characterisation, antimicrobial testing and immune cell assays).

Immune system data were reviewed by considering markers or immune cells analysed (e.g. T cells, macrophages and cytokines) and immune modulation induced by pharmacologically coated surfaces. The effects of pharmacologically active coatings on immune modulation (e.g. changes in cytokine production, immune cell activation and inflammation reduction) were examined. The impact of these coatings on microbial behaviour and immune system interactions in the context of infection prevention, microbial colonisation or tissue healing was also used as a parameter to extract relevant information.

Highlights

- Surface coating with pharmacological molecules offers a novel approach to address these challenges
- The integration of pharmacologically active compounds into surface coatings presents a novel strategy
- Surface coating with pharmacological molecules could enhance surgical safety and efficacy
- Pharmacologically coated surfaces may become integral components of surgery.

CONCLUSION

Surface coatings have revolutionised surgical applications by enhancing the performance, safety and biocompatibility of medical devices, implants and surgical instruments. These coatings offer various advantages, such as reducing friction and wear, preventing corrosion and promoting better instrument manoeuvrability during procedures. Biocompatible coatings minimise the risk of harmful reactions in the body, leading to fewer complications and faster recovery times for patients. In addition, AMCs play a critical role in reducing the risk of infections, particularly in the surgical setting, by preventing bacterial colonisation on medical devices. Moreover, pharmacologically coated surfaces introduce a new level of precision in therapy, allowing for controlled, localised drug delivery to prevent complications such as thrombosis or restenosis and improving the healing process. Graphene-based coatings represent a promising innovation in medical devices due to their excellent corrosion resistance, biocompatibility and potential to enhance bone growth. These materials, when applied to metallic implants, not only protect against degradation but also promote better integration with biological tissues. The development of such advanced coatings ensures that implants and surgical tools are more durable, effective and safer for long-term use. Moreover, anticorrosion and AMCs help to address issues associated with metallic biomaterials, such as ion release, corrosion and the risk of infection, providing a significant step forward in medical device technology. Finally, the evolving field of AMCs, particularly contact-active and biocide-releasing types, has immense potential in reducing HAIs and improving patient outcomes. Whether through the controlled release of biocides or direct contact with pathogens, these coatings offer a strategic method for minimising infection risks in surgical and medical settings. However, challenges remain in ensuring the sustainability and cost-effectiveness of these coatings in real-world applications. Future research into coatings with controlled release mechanisms and responsive properties could lead to even more efficient solutions, making surface coatings a cornerstone of next-generation medical device development. Surface coatings are poised to significantly impact the future of surgery and medical treatments by improving device functionality, patient safety and overall healthcare outcomes.

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REFERENCES

- Kroh M, Schijven MP. Evolution of surgical innovation: Editorship transitions and future directions. *Surg Innov* 2023;30:281-2.
- Bohara S, Suthakorn J. Surface coating of orthopedic implant to enhance the osseointegration and reduction of bacterial colonization: A review. *Biomater Res* 2022;26:26.
- Vallet-Regí M, Lozano D, González B, Izquierdo-Barba I. Biomaterials against bone infection. *Adv Healthc Mater* 2020;9:e2000310.
- Pinelli F, Perale G, Rossi F. Coating and functionalization strategies for nanogels and nanoparticles for selective drug delivery. *Gels* 2020;6:6.
- Amin Yavari S, Castenmiller SM, Van Strijp JAG, Croes M. Combating implant infections: Shifting focus from bacteria to host. *Adv Mater* 2020;32:e2002962.
- Chen X, Zhou J, Qian Y, Zhao L. Antibacterial coatings on orthopaedic implants. *Mater Today Bio* 2023;19:100586.
- Heng L, Kim JS, Song JH, Mun SD. A review on surface finishing techniques for difficult-to-machine ceramics by non-conventional finishing processes. *Materials (Basel)* 2022;15:1227.
- Sabau AS, Jun J, McClurg D. Coating adhesion of a chromate-containing epoxy primer on Al2024-T3 surface processed by laser-interference. *Int J Adhes Adhes* 2020;102:102641.
- Novosel A, Sedlar T, Miklečić J, Turkulin H, Lučić L, Mihulja G, et al. Analysis of bonding mechanisms of various implants and adhesives in laminated oak-wood elements. *Polymers (Basel)* 2022;14:5373.
- Stoffel JT, Yu L. Urinary catheters: Materials, coatings, and recommendations for selection. *Urol Clin North Am* 2024;51:253-62.
- Zhao C, Zhou L, Chiao M, Yang W. Antibacterial hydrogel coating: Strategies in surface chemistry. *Adv Colloid Interface Sci* 2020;285:102280.
- Cajiao Checchin VC, Gonzalez A, Bertuola M, De Mele MA. Multifunctional coatings of phenolic phytochemicals of medical interest: Assembly methods and applications. *Prog Org Coat* 2022;172:107068.
- Hao X, Yang M, Huang W, Zhang F, Gao L, Omran M, et al. Study on drying kinetics of calcium oxide doped zirconia by microwave-assisted drying. *Ceram Int* 2022;48:30430-40.
- Gul RM, Fung K, Doshi BN, Oral E, Muratoglu OK. Surface cross-linked UHMWPE using peroxides. *J Orthop Res* 2017;35:2551-6.
- Iinuma Y, Hirota M, Hayakawa T, Ohkubo C. Surrounding tissue response to surface-treated zirconia implants. *Materials (Basel)* 2019;13:30.
- Andreeva T, Drieschner T, Golovko DS, Lorenz A, Rebner K, Krastev R. Process validation and a new method for quality control of ultrathin polyelectrolyte multilayer coatings. *Colloids Surf A Physicochem Eng Asp* 2023;676:132157.
- Belosi F, Koivisto AJ, Furrxi I, De Ipiña JL, Nicosia A, Ravegnani F, et al. Critical aspects in occupational exposure assessment with different aerosol metrics in an industrial spray coating process. *NanoImpact* 2023;30:100459.
- Wu H, Guo T, Zhou F, Bu J, Yang S, Dai Z, et al. Surface coating prolongs the degradation and maintains the mechanical strength of surgical suture *in vivo*. *Colloids Surf B Biointerfaces* 2022;209:112214.
- Kumari S, Tiyyagura HR, Pottathara YB, Sadasivuni KK, Ponnamma D, Douglas TE, et al. Surface functionalization of chitosan as a coating material for orthopaedic applications: A comprehensive review. *Carbohydr Polym* 2021;255:117487.
- Mateu-Sanz M, Fuenteslópez CV, Uribe-Gomez J, Haugen HJ, Pandit A, Ginebra MP, et al. Redefining biomaterial biocompatibility: Challenges for artificial intelligence and text mining. *Trends Biotechnol* 2023;42:402-17.
- Baçela J, Łabowska MB, Detyna J, Zięty A, Michalak I. Functional coatings for orthodontic archwires-a review. *Materials (Basel)* 2020;13:3257.
- Damen AH, Van Donkelaar CC, Sharma PK, Wan H, Cardinaels R, Schmidt TA, et al. Friction reducing ability of a poly-L-lysine and dopamine modified hyaluronan coating for polycaprolactone cartilage resurfacing implants. *J Biomed Mater Res B Appl Biomater* 2023;111:1523-32.
- Srimanepong V, Skallevoid HE, Khurshid Z, Zafar MS, Rokaya D, Sapkota J. Graphene for antimicrobial and coating application. *Int J Mol Sci* 2022;23:10499.
- Costa RC, Nagay BE, Dini C, Borges MH, Miranda LF, Cordeiro JM, et al. The race for the optimal antimicrobial surface: Perspectives and challenges related to plasma electrolytic oxidation coating for titanium-based implants. *Adv Colloid Interface Sci* 2023;311:102805.
- Roberts TR, Leslie DC, Cap AP, Cancio LC, Batchinsky AI. Tethered-liquid omniphobic surface coating reduces surface thrombogenicity, delays clot formation and decreases clot strength *ex vivo*. *J Biomed Mater Res B Appl Biomater* 2020;108:496-502.
- Junter GA, Thébault P, Lebrun L. Polysaccharide-based antibiofilm surfaces. *Acta Biomater* 2016;30:13-25.
- Babutan I, Lucaci AD, Botiz I. Antimicrobial polymeric structures assembled on surfaces. *Polymers (Basel)* 2021;13:1552.
- Ude CC, Dzidotor GK, Iloeje K, Nair LS, Laurencin CT. Corrosion of metals during use in arthroplasty. *ACS Appl Bio Mater* 2023;6:2029-42.
- Grenadyorov AS, Zhulkov MO, Solovyev AA, Oskomov KV, Semenov VA, Chernyavskiy AM, et al. Surface characterization and biological assessment of corrosion-resistant a-C:H:SiO(x) PACVD coating for Ti-6Al-4V alloy. *Mater Sci Eng C Mater Biol Appl* 2021;123:112002.
- Zhu T, Jiang C, Wang M, Zhu C, Zhao N, Xu J. Skin-inspired double-hydrophobic-coating encapsulated hydrogels with enhanced water retention capacity. *Adv Funct Mater* 2021;31:2102433.

31. Pallavicini P, Preti L, Vita L, Dacarro G, Diaz Fernandez YA, Merli D, *et al.* Fast dissolution of silver nanoparticles at physiological pH. *J Colloid Interface Sci* 2020;563:177-88.
32. Scialla S, Martuscelli G, Nappi F, Singh SS, Iervolino A, Larobina D, *et al.* Trends in managing cardiac and orthopaedic device-associated infections by using therapeutic biomaterials. *Polymers (Basel)* 2021;13:1556.
33. Li M, Wang M, Wei L, Werner A, Liu Y. Biomimetic calcium phosphate coating on medical grade stainless steel improves surface properties and serves as a drug carrier for orthodontic applications. *Dent Mater* 2023;39:152-61.
34. Zhang Y, Zhang L, Duan S, Hu Y, Ding X, Zhang Y, *et al.* Heparinized anticoagulant coatings based on polyphenol-amine inspired chemistry for blood-contacting catheters. *J Mater Chem B* 2022;10:1795-804.
35. Raikar AS, Priya S, Bhilegaonkar SP, Somnache SN, Kalaskar DM. Surface engineering of bioactive coatings for improved stent hemocompatibility: A comprehensive review. *Materials (Basel)* 2023;16:6940.
36. Zhang K, Chooi WH, Liu S, Chin JS, Murray A, Nizetic D, *et al.* Localized delivery of CRISPR/dCas9 via layer-by-layer self-assembling peptide coating on nanofibers for neural tissue engineering. *Biomaterials* 2020;256:120225.
37. Tran PH, Tran TT. Current film coating designs for colon-targeted oral delivery. *Curr Med Chem* 2021;28:1957-69.
38. Talebian S, Mendes B, Coniot J, Farajikhah S, Dehghani F, Li Z, *et al.* Biopolymeric coatings for local release of therapeutics from biomedical implants. *Adv Sci (Weinh)* 2023;10:e2207603.
39. Quarterman JC, Phruttiwanichakun P, Fredericks DC, Salem AK. Zoledronic acid implant coating results in local medullary bone growth. *Mol Pharm* 2022;19:4654-64.
40. Yassin MA, Elkhooly TA, Elsherbiny SM, Reicha FM, Shokeir AA. Facile coating of urinary catheter with bio-inspired antibacterial coating. *Heliyon* 2019;5:e02986.
41. Yang H, Yang Y, Li Y, Hope J, Choo W. Extrinsic conditions for the occurrence and characterizations of self-healing polyurea coatings for improved medical device reliability: A mini review. *ACS Omega* 2023;8:26650-62.
42. Tallury P, Alimohammadi N, Kalachandra S. Poly(ethylene-co-vinyl acetate) copolymer matrix for delivery of chlorhexidine and acyclovir drugs for use in the oral environment: Effect of drug combination, copolymer composition and coating on the drug release rate. *Dent Mater* 2007;23:404-9.
43. Prasad K, Bazaka O, Chua M, Rochford M, Fedrick L, Spoor J, *et al.* Metallic biomaterials: Current challenges and opportunities. *Materials (Basel)* 2017;10:884.
44. McMahon RE, Ma J, Verkhoturov SV, Munoz-Pinto D, Karaman I, Rubitschek F, *et al.* A comparative study of the cytotoxicity and corrosion resistance of nickel-titanium and titanium-niobium shape memory alloys. *Acta Biomater* 2012;8:2863-70.
45. Goryczka T, Szaraniec B. Characterization of polylactide layer deposited on ni-ti shape memory alloy. *J Mater Eng Perform* 2014;23:2682-6.
46. Williams RP, Rinchuse DJ, Zullo TG. Perceptions of midline deviations among different facial types. *Am J Orthod Dentofacial Orthop* 2014;145:249-55.
47. Li P, Wu G, Xu R, Wang W, Wu S, Yeung KW, *et al.* *In vitro* corrosion inhibition on biomedical shape memory alloy by plasma-polymerized allylamine film. *Mater Lett* 2012;89:51-4.
48. Mazumder MM, Mehta JL, Mazumder NN, Trigwell S, Sharma R, De S. Encased stent for rapid endothelialization for preventing restenosis. 20040225346A1. Patent; 2004. p. e00489-12.
49. Schellhammer F, Walter M, Berlis A, Bloss HG, Wellens E, Schumacher M. Polyethylene terephthalate and polyurethane coatings for endovascular stents: Preliminary results in canine experimental arteriovenous fistulas. *Radiology* 1999;211:169-75.
50. Villermaux F, Tabrizian M, Yahia L, Czeremuszkina G, Piron DL. Corrosion resistance improvement of NiTi osteosynthesis staples by plasma polymerized tetrafluoroethylene coating. *Biomed Mater Eng* 1996;6:241-54.
51. Tepe G, Schmehl J, Wendel HP, Schaffner S, Heller S, Gianotti M, *et al.* Reduced thrombogenicity of nitinol stents--*in vitro* evaluation of different surface modifications and coatings. *Biomaterials* 2006;27:643-50.
52. Anjum SS, Rao J, Nicholls JR. Polymer (PTFE) and shape memory alloy (NITI) intercalated nano-biocomposites. *Mater Sci Eng* 2012;40:012006.
53. De Jesús C, Cruz GJ, Olayo MG, Gómez LM, López-Gracia OG. Coatings by plasmas of pyrrole on nitinol and stainless steel substrates. *Superf Vacío* 2012;25:157-60.
54. Yang MR, Wu SK. Dc plasma-polymerized hexamethyldisilazane coatings of an equiatomic tni shape memory alloy. *Surf Coat Technol* 2000;127:274-81.
55. Bhattacharyya A, Dervishi E, Berry B, Viswanathan T, Bourdo S, Kim H, *et al.* Energy efficient graphite-polyurethane electrically conductive coatings for thermally actuated smart materials. *Smart Mater Struct* 2006;15:S187.
56. Lin WS, Metz MJ, Pollini A, Ntounis A, Morton D. Digital data acquisition for a CAD/CAM-fabricated titanium framework and zirconium oxide restorations for an implant-supported fixed complete dental prosthesis. *J Prosthet Dent* 2014;112:1324-9.
57. Carroll WM, Rochev Y, Clarke B, Burke M, Bradley DJ, Plumley DL. Influence of nitinol wire surface preparation procedures, on cell surface interactions and polymer coating adherence, materials and processes for medical devices conference. Anaheim, CA, USA: ASM International; 2004. p. 63-8.
58. Rokaya D, Srimaneepong V, Qin J. Modification of titanium alloys for dental applications. In: Rajendran S, Naushad M, Durgalakshmi D, Lichtfouse E, editors. *Metal, metal oxides and metal sulphides for biomedical applications*. Cham, Switzerland: Springer International Publishing; 2021. p. 51-82.
59. Raza MA, Rehman ZU, Ghauri FA, Ahmad A, Ahmad R, Raffi M. Corrosion study of electrophoretically deposited graphene oxide coatings on copper metal. *Thin Solid Films* 2016;620:150-9.
60. Nayak PK, Hsu CJ, Wang SC, Sung JC, Huang JL. Graphene coated Ni films: A protective coating. *Thin Solid Films* 2013;529:312-6.
61. Catt K, Li H, Cui XT. Poly (3,4-ethylenedioxythiophene) graphene oxide composite coatings for controlling magnesium

- implant corrosion. *Acta Biomater* 2017;48:530-40.
62. Asgar H, Deen KM, Rahman ZU, Shah UH, Raza MA, Haider W. Functionalized graphene oxide coating on Ti6Al4V alloy for improved biocompatibility and corrosion resistance. *Mater Sci Eng C Mater Biol Appl* 2019;94:920-8.
 63. Zhou Q, Yang P, Li X, Liu H, Ge S. Bioactivity of periodontal ligament stem cells on sodium titanate coated with graphene oxide. *Sci Rep* 2016;6:19343.
 64. Catt K, Li H, Hoang V, Beard R, Cui XT. Self-powered therapeutic release from conducting polymer/graphene oxide films on magnesium. *Nanomedicine* 2018;14:2495-503.
 65. Singh BP, Nayak S, Nanda KK, Jena BK, Bhattacharjee S, Besra L. The production of a corrosion resistant graphene reinforced composite coating on copper by electrophoretic deposition. *Carbon* 2013;61:47-56.
 66. Hikku GS, Jeyasubramanian K, Venugopal A, Ghosh R. Corrosion resistance behaviour of graphene/polyvinyl alcohol nanocomposite coating for aluminium-2219 alloy. *J Alloys Compd* 2017;716:259-69.
 67. Suo L, Jiang N, Wang Y, Wang P, Chen J, Pei X, *et al.* The enhancement of osseointegration using a graphene oxide/chitosan/hydroxyapatite composite coating on titanium fabricated by electrophoretic deposition. *J Biomed Mater Res B Appl Biomater* 2019;107:635-45.
 68. Li K, Wang C, Yan J, Zhang Q, Dang B, Wang Z, *et al.* Evaluation of the osteogenesis and osseointegration of titanium alloys coated with graphene: An *in vivo* study. *Sci Rep* 2018;8:1843.
 69. Rosa V, Rodríguez-Lozano FJ, Min K. 22-Graphene to improve the physicochemical properties and bioactivity of the cements. In: Khurshid Z, Najeeb S, Zafar MS, Sefat F, editors. *Advanced dental biomaterials*. Soston, UK: Woodhead Publishing; 2019. p. 599-614.
 70. Nair M, Nancy D, Krishnan AG, Anjusree GS, Vadukumpully S, Nair SV. Graphene oxide nanoflakes incorporated gelatin-hydroxyapatite scaffolds enhance osteogenic differentiation of human mesenchymal stem cells. *Nanotechnology* 2015;26:161001.
 71. Liu Y, Huang J, Li H. Synthesis of hydroxyapatite-reduced graphite oxide nanocomposites for biomedical applications: Oriented nucleation and epitaxial growth of hydroxyapatite. *J Mater Chem B* 2013;1:1826-34.
 72. Xie H, Chua M, Islam I, Bentini R, Cao T, Viana-Gomes JC, *et al.* Cvd-grown monolayer graphene induces osteogenic but not odontoblastic differentiation of dental pulp stem cells. *Dent Mater* 2017;33:e13-21.
 73. Xie H, Cao T, Gomes JV, Castro Neto AH, Rosa V. Two and three-dimensional graphene substrates to magnify osteogenic differentiation of periodontal ligament stem cells. *Carbon* 2015;93:266-75.
 74. Nishida E, Miyaji H, Kato A, Takita H, Iwanaga T, Momose T, *et al.* Graphene oxide scaffold accelerates cellular proliferative response and alveolar bone healing of tooth extraction socket. *Int J Nanomedicine* 2016;11:2265-77.
 75. Francolini I, Vuotto C, Piozzi A, Donelli G. Antifouling and antimicrobial biomaterials: An overview. *APMIS* 2017;125:392-417.
 76. Gao G, Lange D, Hilpert K, Kindrachuk J, Zou Y, Cheng JT, *et al.* The biocompatibility and biofilm resistance of implant coatings based on hydrophilic polymer brushes conjugated with antimicrobial peptides. *Biomaterials* 2011;32:3899-909.
 77. Siedenbiedel F, Tiller JC. Antimicrobial polymers in solution and on surfaces: Overview and functional principles. *Polymers* 2012;4:46-71.
 78. Zasloff M. Antimicrobial peptides of multicellular organisms. *Nature* 2002;415:389-95.
 79. Zander ZK, Becker ML. Antimicrobial and antifouling strategies for polymeric medical devices. *ACS Macro Lett* 2018;7:16-25.
 80. Mathew RT. Greener surface anchoring anti-bacterials. New Zealand: University of Auckland: Auckland; 2019. p. 48-52.
 81. Saseendran Nair S, Anand V, De Silva K, Wiles S, Swift S. The antibacterial potency and antibacterial mechanism of a commercially available surface-anchoring quaternary ammonium salt (SAQAS)-based biocide *in vitro*. *J Appl Microbiol* 2022;133:2583-98.
 82. Sambhy V, Peterson BR, Sen A. Multifunctional silane polymers for persistent surface derivatization and their antimicrobial properties. *Langmuir* 2008;24:7549-58.
 83. Legido-Quigley C, Marlin ND, Melin V, Manz A, Smith NW. Advances in capillary electrochromatography and micro-high performance liquid chromatography monolithic columns for separation science. *Electrophoresis* 2003;24:917-44.
 84. Robertson J, Dalton J, Wiles S, Gizdavic-Nikolaidis M, Swift S. The tuberculocidal activity of polyaniline and functionalised polyanilines. *PeerJ* 2016;4:e2795.
 85. Robertson J, Gizdavic-Nikolaidis M, Swift S. Investigation of polyaniline and a functionalised derivative as antimicrobial additives to create contamination resistant surfaces. *Materials (Basel)* 2018;11:436.
 86. Robertson J, Gizdavic-Nikolaidis M, Nieuwoudt MK, Swift S. The antimicrobial action of polyaniline involves production of oxidative stress while functionalisation of polyaniline introduces additional mechanisms. *PeerJ* 2018;6:e5135.
 87. Marija Gizdavic-Nikolaidis GB, Zujovic Z. The synthesis, physical properties, bioactivity and potential applications of polyanilines. Vol. 1. Newcastle upon Tyne, UK: Cambridge Scholars Publishing; 2018. p. 52-67.
 88. Gizdavic-Nikolaidis MR, Bennett JR, Swift S, Eastal AJ, Ambrose M. Broad spectrum antimicrobial activity of functionalized polyanilines. *Acta Biomater* 2011;7:4204-9.
 89. Rigo S, Cai C, Gunkel-Grabole G, Maurizi L, Zhang X, Xu J, *et al.* Nanoscience-based strategies to engineer antimicrobial surfaces. *Adv Sci (Weinh)* 2018;5:1700892.
 90. Warnes SL, Highmore CJ, Keevil CW. Horizontal transfer of antibiotic resistance genes on abiotic touch surfaces: Implications for public health. *mBio* 2012;3:e00489-12.

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