Chapter 6
Engineering of Dental Titanium Implants and Their Coating Techniques

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1 Introduction

Implants provide a functional restoration of edentulous regions along the alveolar crest; thus, material selection should be durable for functional loading and biocompatible to achieve osseointegration. Long-term implant success is predicated on successful osseointegration, which provides the secondary retention for the span of the implant. Osseointegration is defined as a functional ankylosis of a load-bearing artificial implant [1].

Titanium is a favorable biomaterial for dental implants because of its rigidity, biocompatibility, and hydrophilicity properties. It induces bioactivity via electronegative potential [2]. It is resistant to a variety of forces and maintains a similar coefficient of expansion to bone, making it an ideal post material for load bearing in dental implantology. Innate properties of titanium can be bolstered with use of coating techniques, manipulating the microenvironment of the surgical site upon placement and through healing [3].

A controlled immune response, high rate of angiogenesis, and bioactivity are conducive to osseointegration; furthermore, the intimacy in which bone apatite is formed to the implant surface determines the seal of the implant, thus reducing incidence of bacterial adhesion [4]. A multitude of clinical presentations provide challenges to favorable wound healing conditions. Functionalization of titanium implant surfaces allows further control over osseointegration of the implant, providing wider patient selection for the restoration of function [4].

Surface modification is subdivided into two methodologies: additive and subtractive [5]. Additive modifications include coating or impregnation of a material on

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the titanium surface. Subtractive methods remove material to roughen the surface, increasing porosity. Grit blasting, etching, and ablation are some examples. These methods can be combined to adjust the interface of titanium, leaving a wide range of possibilities for functionalization and more dimension planning an implant design. This article will focus on additive surface modifications of titanium, their biomechanics, and schema.

The chapter will also discuss the benefits and limitations of coating techniques and coating substrates, both conventional and prospective. The article is organized by substrate, as coating techniques may be used for a variety of materials; thus, a brief overview of the scheme and application of coating methods is included, with explanation of the advantages and limitations of these methods. Prospective studies are compared with conventional techniques to emphasize the future study.

2 Overview

Surface coating may be organic, inorganic, or a combination of both [5]. Organic coats consist of polymeric or biomimetic films deposed at the surface. Inorganic coats in implantology often consist of metals or ceramics. These coats can be assembled at a molecular level, forming highly organized surface topographies at a nanoscale. Many of these materials, both organic and inorganic, accept nanoparticles sterically or chemically, adding more control to a surface coating scheme. Furthermore, assembly of these coats may be implemented to be more inclusive, offering a multitude of alteration to the biochemistry at the implant surface.

Surface coats ideally adhere to the titanium implant surface in a stable and predictable manner after processing, exhibiting minimization of cytotoxicity and genotoxicity, efficacy of pharmaceutical reagent with optimal, sustained diffusion of incorporated pharmacy [4, 6]. Defects during processing may lead to premature, bulk fracturing of coat material in commercially used coating methods, such as plasma spraying, inducing undesired inflammation. Increased bond strength between the coat and implant reduces incidence of these unwanted outcomes. Ultimately, an ideal coat is conducive to apatite formation intimately adhering to the surface. Schematics for implant coats ideally allow intercalation of forming apatite or factor in metabolism of the coating material to reorganize the bone–implant interface for optimal osseointegration [7].

Peri-implantitis in the first year of implant placement constitutes 10% of premature failures, rendering it the leading cause of implant failure [8]. Reinforcing implants with antimicrobial potential is accomplished with the sustained release of antimicrobial medications for long-term healing or weigh the competitive adherence to the implant surface in favor of osteoblastic activity [9]. Antimicrobial medications can be bactericidal, bacteriostatic, or primers for immune response. Chemotaxis and the provision of an adherent media promote cell adhesion. These factors may be intrinsic properties of surface coating materials; however, nanoparticles localized at the implant surface allow the opportunity to introduce reagents to

the surgical site. Because these nanoparticles are readily metabolized, they are often impregnated within a slowly metabolized matrix for sustained release overtime, lest they be exhausted prematurely. Materials such as hydroxyapatite (HA), graphene oxide, and chitosan offer the capacity to be impregnated by these nanoparticles [10–12].

3 Implant Coating Materials and Techniques

Biochemical substrates are biomimetic materials at the implant surface, creating a microenvironment that is primed for osseointegration. In conceiving these materials, there is a focus in mimicry of pre-existing compositions for optimal biocompatibility [13]. This can include the localization of plasma proteins and extracellular matrix (ECM) proteins to expedite wound healing, as well mimicry of bony architecture, which is accomplished by HA coating [14]. The challenge is in immobilizing and localizing these biochemical agents so that they aid in osseointegration reliably over time [15].

HA constitutes the inorganic matrix of bone, rendering a biomimetic environment on the surface of the implant. Localization of HA promotes bone morphogenic protein (BMP) in the area. Thus, HA is osteoinductive and improves the outcome of peri-implant osteogenesis. Clinical trials of full zirconia implants demonstrated failure due to its brittleness and inferior electronegative potential when compared to titanium [4].

Ideal coating methods for HA yield a high adhesion strength to the implant surface HA in a thin, uniform layer [16]. Furthermore, HA's capacity for drug delivery has prompted the investigation of coating mechanisms conducive to processing particles that would otherwise be disintegrated or denatured in processing. HA has multiple phases but is optimal in its crystalline phase; therefore, sintering is required for coating techniques that apply high heat and subject HA to phase changes [3].

Quercitrin is a naturally occurring flavonoid, demonstrating improved soft tissue integration, as well as anti-inflammatory and antioxidant properties, mimicking interleukin-1-beta. Excessive inflammation delays healing time; thus, optimized quercitrin-nanocoated titanium surfaces demonstrate enhanced mesenchymal stem cell recruitment and increased rate of osteoblast differentiation. This is supplemented by the inhibition of COX2 expression locally, decreasing PGE2. It also resolves inflammation through the reduction of oxidative stress at the surgical site. Furthermore, enhanced population of cellular activity at the implant site competes with bacteria, decreasing incidence of peri-implantitis [19]. Quercitrin demonstrates positive effects on cells, encouraging expression of hard and soft tissues, and may be used in conjunction with other biomaterials to enhance the rate of osseointegration.

Chitosan is a stable, naturally occurring polysaccharide that promotes the expression of extracellular matrix proteins in osteoblasts and chondrocytes [12]. It is found in normal mammalian tissue, rendering it biocompatible. It contains a primary

amino group at the 2-position of each polymer subunit, allowing it to be easily conjugated [20]; thus, it may readily be used to deliver nanoparticles in conjunction with its intrinsic properties. In particular, conjugation with silver bolsters the chitosan with the beneficial antimicrobial effects of silver. Chitosan is also compatible with various matrices, including HA and graphene [11, 20, 21].

Chlorhexidine (CHX) is widely used in dentistry as an effective, broad-spectrum antiseptic agent. While CHX readily adsorbs to the implant surface, it is rapidly depleted—acting as a short-term, localized antimicrobial. Modification of this agent to CHX hexametaphosphate (HMP) demonstrates aggregation to a porous implant surface that provides a more sustained release [9].

Inorganic substrates, especially metals, have intrinsic properties providing antimicrobial effects. They also retain electronegative potential, promoting chemotaxis. Many of these materials can be conjugated onto a coating matrix to supplement it with these unique properties.

Niobium (Nb) is a biocompatible, anti-erosive element [22, 23] and can be applied to titanium in a single-phased subniobium with a conjugate atom. In this manner, a variety of Nb-based films may be produced with oxide, carbide, and nitride conjugates. Of these, NbC proves to be most optimal in vitro, forming a nanocomposite film with great protective efficiency [24], high corrosion resistance, and low coefficient of friction conducive to tribological performance when compared to other Nb film types [25].

Magnetron sputtering (see Table 6.1) of Nb thin films results in amorphous, crack-free coats with good adherence [26].

Graphene oxide demonstrates good mechanical properties with high biocompatibility and antibacterial properties. Its capacity for drug delivery and biosensing has garnered it recent attention in tissue engineering [27].

Graphene may be incorporated in HA coats to reinforce HA. This reinforced GO/HA coat exhibits enhanced physical properties when compared to HA alone [28]. It is also recipient to further addition of osteogenic materials [29].

PMMA transfer is used to coat graphene oxide in a uniform, minimally defective manner. A graphene sheet is seeded on polished Cu foil and treated with coated with a layer of PMMA. This sample is etched to clear the copper, and the unreacted PMMA/graphene is fished with a hexagonal boron nitride and silicon dioxide chip. The PMMA is removed with an organic solvent and Ar/H_2 environment. This new sample can be annealed to a target in an ultrahigh-vacuum chamber [30].

4 Immobilization

Immobilization describes the processes by which a biomolecular or nanoparticle substrate is arrested at a target surface. This can be accomplished via adsorption, covalent coupling, and physical entrapment. While whole growth factor proteins immobilized at the titanium surface demonstrate improved healing, research is focusing on the production of select GF peptide sequences, such as those that

Table 6.1 HA deposition methods

Deposition methods	Description	Adhesion strength (MPa)	Advantages	Disadvantages	References
Plasma spraying	Coating particle is heated into a molten state in a plasma flame and accelerated to the surface of the implant	25	Simple and efficient Low cost Rapid deposition	Highly permeable Environmentally sensitive High temperature processing Sintering required	[3, 4, 10, 13, 17]
Sol-gel technique	Coating particle added to solvent, which is hydrolyzed, condensing the particle into a thin layer. This is applied to the surface. Gel is heat treated and melts away, leaving coating particle	26	High uniformity Thin coating at a low temperature Low cost		[3, 4, 10, 17]
Electrophoretic deposition	Implant is placed in electrophoretic bath, acting as anode upon which electrolytes can be deposited	18	Simple set-up High deposition rate Low cost	Prone to bulk fracture Sintering required	[4, 8, 10, 18]
Micro-arc oxidation	Pulsed DC field applied to Ti in an aqueous solution with the addition of electrolytes that deposit during MAO	44	Economical Environmentally friendly Increased corrosion resistance		[8, 10, 17, 18]
Magnetron sputtering	Magnetic field of trapped particles is brought near a target electrode target. Particles are emitted and coat target in a thin, uniform layer	80	Dense and uniform Low temperature processing High purity and adhesion strength	Time-consuming Low deposition rate Not yet conducive to complex structures, like threaded implants	[8, 10, 18]

promote growth [31, 32]. Nanoparticles, on the other hand, maintain well-researched, intrinsic properties which can contribute to chemistry of the coat. They can also be impregnated into implant surfaces and their coats to add additional chemical properties to the surface with negligible alteration to the surface topography [33].

Adsorption is the simplest method—the target is coated in a solution of proteins. This yields low surface loading; furthermore, immobilized substrate is easily exhausted.

Covalent coupling offers superior surface loading and improved control over the outcome of immobilization. Overall, nanocomposites, quercitrin, chitosan, and HA are all capable of covalent coupling. The substrate to be immobilized is limited by its interaction with the biomolecule to be linked.

Physical entrapment places the substrate in a physical barrier, such as a synthetic lacuna. HA provides a matrix in which physical entrapment of proteins and nanoparticles can be planned. This process is less predictable, but the range of substrate is extensive, since immobilization is not dependent on chemical interaction.

4.1 Peptide Immobilization

Peptide utility in biomaterials provides accelerated synthesis with supplement of the specific peptide sequences conducive to desired osteoconductive effects. Antimicrobial peptides offer broad-spectrum potency against bacteria with lowered chance of resistance when compared to conventional antibiotics [34]. It is well documented that introduction of growth factors improves osteogenic effects.

Silanes are widely used cross-linkers for immobilizing bioactive peptide sequences. They also have the added effect of expressing osteogenic properties intrinsically [35].

4.2 Nanoparticles

Silver (Ag) is one of the most well-researched antimicrobials. In all metallic, silver nitrate and silver sulfadiazine configurations, this element demonstrates stable and broad antimicrobial properties, with low toxicity to patients [36].

Zinc oxide (ZnO) is a biocompatible material that demonstrates antimicrobial properties, with wide commercial use. Its proposed mechanism is adherence to the microbes surface, attracting hydrogen peroxides due to electrostatic forces [9, 37].

Copper oxide (CuO) demonstrates a low cost solution to providing an antibacterial and antifungal nanocoat. They can be covalently localized to nanocomposites [38].

Al_2O_3 TiO_2 nanotubes: One study found that osteoblast adhesion increases on nanophase metals when compared to conventionally sized particles [39]. TiO_2 is intrinsically more electronegative when compared to HA and can be arranged in

nanotubes, which exhibit high surface-to-volume ratio when compared conventional roughening modifications. TiO_2 also exhibits a more intimate bond than when compared to conventional HA coats. Because apatite arranges itself at a nanoscale, combined with the properties of the metal itself, uniform apatite precipitation is observed on the surface of nanofibrous surfaces, comparable to the intimacy of biointegration demonstrated in HA-coated biomaterials. Furthermore, the surface area to volume ratio is significantly improved over conventional grit blasting, improving bone bonding in vivo [40].

Positive template-assisted fabrication utilizes sol-gel deposition to deposit TiO_2 on a ZnO-nanorod template. This structure can be deposited to the implant surface and the ZnO selectively removed with chemical etchants, leaving the surface with the nanotubes only. This approach yields asymmetrical tubes with open ends [41].

Negative template-assisted fabrication utilizes an anodic aluminum oxide membrane that consists of monodisperse cylindrical pores through which nanotubes are deposited via sol-gel deposition. The resulting nanotubes are even [41].

In *anodization* method, the implant is anodized in an aqueous solution containing 0.5–3.5 wt% hydrofluoric acid; the nanotubes arrange themselves in varying lengths, resulting in an amorphous matrix. The nanotubes are annealed to return them to their crystalline state, which can cause sintering of the nanotubes and thus the collapse of the nanotubular structure. Therefore, this method is sensitive to the annealing process [41].

Hydrothermal treatment is the process by which TiO_2 particles are synthesized into nanotubes. Hydrothermal treatment of nanoparticles with NaOH breaks their bonds so they can reform as sheets. An HCL wash removes the electrostatic charge of the sheets, causing them to roll up into nanotubes. These nanotubes may then be used to coat implant surfaces. This method reports long reaction times with nanotubes of random alignment due to excessive intercalation from NaOH [41].

Nanocrystalline diamond particles are hard, inert, and highly thermally conductive. Corrosion resistance and biotolerance lends it to providing a selective protective barrier, preventing the release of metals to the body. Nanocrystalline coats may provide osteoconductivity, antimicrobial properties, and corrosion resistance [42]. An animal study in the mandibles of pigs demonstrated immobilized BMP-2 on nanocrystalline coats that were unaffected when exposed to radiation, which may preserve osteoinductive potential in irradiated bone [43]. They are also wear resistant, making them potential coats for load-bearing implants [44].

5 Discussion and Future Trends

Additive surface modifications are beneficial in that they offer control of localized chemistry while maintaining the properties that make titanium a favorable implant post-material [17]. The goal is to enhance the capacity for secondary retention, ultimately leading to long-term implant success. To this end, adoption of wound-healing elements, especially in the form of fibroblast adoption and differentiation,

and antimicrobial activity are favorable [7]. Furthermore, reduction of inflammation at the surgical site expedites wound healing [19].

To this, the composition of surface coating is designed to enhance these properties. Research on surface coating lends itself to the capacity in which these materials may be combined for strategic enhancement of favorable local biochemistry overtime [7]. Ideal coats are biomimetic matrices capable of releasing beneficial particles to the surgical site, promoting healing, and reducing incidence of inflammation and peri-implantitis.

The challenges of surface coating are derived from mechanical properties between the implant and coat interface. Alternatives to HA coating are being investigated due to its poor adherence to titanium. Because of this, TiO_2 nanotubes present as a prospective surface modification [41, 45].

Nanoparticles are unique in that their properties are intrinsic and may be incorporated to supplement a coating material. While they can readily impregnate the implant surface, a slowly dissolving matrix is preferable for sustained release. Optimization of this strategy drives research in supplementing coating materials, such as HA, TiO_2, and graphene. Chemical conjugation and mechanical retention in synthetic lacunae are the approaches that facilitate this action.

Prospective Coating Materials The interaction of titanium with a variety of novel biomaterials is being investigated. Nanocomposites and their unique properties are influencing new schemes for additive surface modifications. Graphene demonstrates unique approach to drug delivery—its high surface area to volume ratio offers functionalized capacity to surfaces to which it is applied [46]. This significant increase in surface area could have a multitude of implications for the future of surface modification. Graphene may be hybridized with metals and metal oxides. One study demonstrated graphene/zinc oxide nanocomposite films offer profound antimicrobial properties [47]. Research in hybridization of various other nanoparticles may offer more insight on the utility of this material. Currently, graphene lacks an efficient method to be applied to three-dimensional, complex objects, such as a dental screw-retained implant. Nb as a surface coating has garnered interest in bioengineering due to its biocompatibility and increased mitochondrial activity in comparison to cells cultured on titanium [48]. Furthermore, it has the capacity to form nanocomposites. Another study demonstrated intrinsic capacity of crystalline NbN and amorphous Nb_2O_5 coatings for cementoblast attachment [49]. Overall, graphene forms as a monolayer with considerably more corrosive resistance than Nb nanocomposites. A comparison of graphene and Nb's tribology may offer insight on the long-term properties of these materials in function [50]. TiO_2 nanotubes can form a high surface area to volume ratio that increases at the surface of the implant, but not in the organization with which graphene coats are capable. However, the efficacy of TiO_2 nanotubes as a surface treatment is well documented. Nanocrystalline diamond also has properties comparable to nanocomposites with similar capacity for covalent immobilization.

Prospects in coating schematics can be seen in the formulation of coats with multifunctionality [51]. Co-immobilization of a multitude of beneficial peptides

and nanoparticles allows a wide range of osteogenic and antimicrobial potential. Furthermore, coating materials can reinforce the mechanical properties of one another. One study successfully coated titanium implants with a HA/chitosan/graphene coat [11]. Graphene reinforces the brittle nature of HA, while chitosan, along with its intrinsic properties, may be conjugated with nanoparticles for drug delivery. Delivery of this coating complex indicates the dimension with which additive modifications can enhance titanium implant success. The integrity of these materials in coexistence is not well documented. While graphene may reinforce the integrity of HA, stress testing with a multitude of these materials has little evidence. Nanocrystalline diamond demonstrates potential as a nanofiller in biopolymeric matrices [52]. Optimization and cross reactions between immobilized nanoparticles and peptides require further investigation. Histocompatibility of these materials should also be investigated. Further testing should be performed on the integrity of these materials in vivo. Both Nb and graphene can be deposited with similar methodologies. It has been suggested that hybridization is possible, compounding their anticorrosive and osteoconductive properties [26]. Overall, the future of additive surface coating is focused on optimization of multifactorial coats that demonstrate antimicrobial and osteoconductive properties.

6 Summary

HA has continually been the most important material in coating of titanium implants. HA is being developed in new ways to adapt more dimensions for its applications. A more reliable, commercial method of coating dental implants with HA is underway. Ion magnetron sputtering is a promising delivery of a controlled, even coat with significantly improved bond strength when compared to conventional HA coating mechanisms. This coating method is still in development.

Research in nanocomposites and their unique properties will play a key role in the development of prospective coating schematics. Based on enhanced tribology and osteoconductive potential of Nb and graphene-based nanocomposites, they are worth investigating. These materials also offer many advantages to formulating drug delivery strategies in more organized manner. Currently, stress testing and animal studies have little evidence in these multifunctional coating schemes. Understanding how the materials interact with each other needs to be better understood.

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