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Osseointegration, Dental implants, Surface modification, Nanotechnology, Bioactive coatings, Implant surface engineering, Biomaterials

Authors

Dr. Prabhakar Naik Eslavat^{1*}
MDS Post Graduate, Department of Prosthodontics, Pacific Dental College and Research Center, Rajasthan, Udaipur-313001 Specialization: Prosthodontics ORCID ID: 0009-0005-4203-8677 Email ID: doctorprabhakar7@gmail.com

Dr Himabindu Ravella²,
MDS, Professor, Department of Prosthodontics, Gitam dental college and Hospital, Visakhapatnam, AP ORCID ID: 0009 0000 8387 1730 Email ID: ravellahimabindu28@gmail.com

Dr Shilpa Khullar Sood³
Professor & Head, Department of Dentistry, Amrita Vishwa Vidya Peetham, Faridabad Campus, Haryana 121002 Specialization: Prosthodontics and Maxillofacial Prosthetics ORCID ID: 0009-0004-7936-3185 Email ID: shilpakhullar@gmail.com

Dr. Abarna Jawahar⁴
Senior Lecturer, Department of Oral Medicine and Radiology, Sree Balaji Dental College & Hospital Bharath Institute of Higher Education and Research (BIHER) ORCID ID - 0000-0001-7937-3923 Email ID: drabarnajawahar@gmail.com

Dr. Sanpreet Singh Sachdev⁵
Assistant Professor, M.D.S. Oral and Maxillofacial Pathology, Department of Oral Pathology and Microbiology, Bharati Vidyapeeth (Deemed to be University) Dental College and Hospital, Navi Mumbai, India Email ID: sanpreet.singh@bharativedyapeeth.edu ORCID ID: 0000-0001-7655-8180

Dr. Shashvat Priyam Khare⁶
Assistant Professor, Department of Physical Education, TMIMT College of Physical Education, Teerthankar Mahaveer University, Moradabad, Uttar Pradesh, India
Specialization: Sports Biomechanics and Exercise Physiology.
Email ID: Shashvat.physicaleducation@tmu.ac.in
ORCID ID: <https://orcid.org/0000-0002-6771-3860>

Preeti Prangya Sahoo⁷
Intern, Specialization: BDS, Department Of Dental, Kalinga institute of dental sciences, KIIT University, BBSR, 751024, ODISHA ORCID ID: 0009-0000-3076-8457 Email ID: preetijun26@gmail.com

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Advances in Dental Implant Surface Technologies for Improved Osseointegration

Abstract

Dental implant success is fundamentally dependent on effective osseointegration, a process governed by complex interactions between implant surfaces and the biological environment. Over recent decades, significant advancements in surface engineering have transformed implant design from passive structural components to biologically active systems that actively promote bone integration and long-term stability. This review provides a comprehensive overview of emerging dental implant surface technologies and their role in enhancing osseointegration. Surface modifications at micro- and nano-scales have been shown to significantly influence protein adsorption, cellular adhesion, and osteogenic differentiation. Techniques such as sandblasting, acid etching, anodization, plasma treatment, and laser texturing have improved surface roughness, wettability, and energy, thereby enhancing early healing responses. In addition, bioactive and functionalized surfaces incorporating antimicrobial agents, growth factors, and immunomodulatory materials have demonstrated the ability to simultaneously promote bone formation and reduce the risk of peri-implant infections. Advancements in manufacturing technologies, including additive manufacturing and sol-gel coatings, have enabled the development of customized and multifunctional implant surfaces. Furthermore, alternative biomaterials such as zirconia and polyetherketone have expanded the scope of implant applications, offering improved aesthetic and mechanical properties. Preclinical and clinical evaluations consistently indicate that optimized surface characteristics lead to improved bone-to-implant contact and long-term implant stability. Despite these advancements, challenges remain in standardizing surface modification techniques and translating experimental findings into clinical practice. Future directions focus on the development of smart, biomimetic, and patient-specific implant surfaces to further enhance clinical outcomes.

1. Introduction

The fundamental biological mechanism by which dental implants perform well and can be referred to as the basic mechanism of dental implant success is known as the process of Osseointegration, which involves a direct straight stable interface of the living bone and dental implant surface devoid of the formation of an intervening soft tissue [1]. The long-term success of implant therapy has been significantly increased during the past several decades, though even in physiological and pathological states, the stability of the bone-implant interface is the key to success. Poor osseointegration failures have remained clinical problems that continue to exist today in the form of patients with compromised systemic health or bone quality.

Peri-implant diseases, especially peri-implantitis disease is regarded as a leading cause of implant failure and is directly associated with the colonization by microbes and reactions of the host immune system [2]. Biofilms of pathogens that develop on the surface of implants have an impact on the local bone homeostasis which in turn trigger inflammatory cascade that induce local bone loss. This is a two-fold task of achieving rapid osseointegration and inhibiting bacterial attachment which has sparked a lot of research on how best to modify the nature of the dental implants surface.

Surface engineering is an element of determination of the early biological responses modulation following the implant placement. Initial contact of the implant surface with the biological fluids results in the adsorption of proteins which consequently controls the cellular adhesion, cell proliferation and cell differentiation [3]. These early events are also very sensitive to the surface features like roughness, surface chemistry and energy and therefore it is worthwhile to come up with an active design of implant surfaces that will induce osteogenic reactions. The development of biomaterials science has enabled arising surfaces not so much passively on the whole, but will be capable to mediate biological processes on the molecular scale.

Traditionally, dental implants were manufactured having smooth machined faces, which have acquired limited bone to implant interfaces with reducing integration rates. Such methods as sandblasting and acid etching led to the introduction of moderately rough surfaces which became a significant breakthrough in the sphere of implantology because such kind of modification enhanced mechanical interlocking and early stability [4]. Such advances notwithstanding, traditional roughened surfaces may be nothing less than universal and in those hard clinical scenarios where some or all of the aforementioned issues may be present, like lessened bone density or systemic conditions that may impair the healing process, they are notably poor. The clinical constraints that have come along with compromised osseointegration have triggered efforts of more advanced approaches of surface modification. Impaired or delayed bone healing is evident in patients with diabetes, osteoporosis or a smoking background and as such they need implant surfaces that can overpower their biological shortcomings [6]. This has led to current research efforts aimed at development of surfaces that have multiple functionalities like enhanced osteoconductivity, anti-microbial activity and immunomodulatory properties.

The development of the surface technologies of implants has also focused on nano-engineering due to the potential of recreating the hierarchical structure of natural bone. Surface topographies nano-scale influence the adsorption of proteins and cellular signalling pathways, and optimise osteoblast differentiation and bone formation [7]. Such coating improves a biomimetic milieu through which Deminerous and stable osseointegration is achievable and during certain critical periods of healing particularly during the initial stages. One of the biggest advancements in replacing the conventional adjustments made at the micro-scale is the addition of nano-topographical cues.

Other factors that are important in defining the biological outcomes are surface wettability and energy. Hydrophilic surfaces of implantations have been demonstrated to enhance the adsorption and cellular adherence of proteins leading to the acceleration of healing and promoting the adhesion of more bone to the implant [8]. Surface chemistry and topographical synergies have significant functions in optimization of

cell responses since they influence the quantity and quality of tissue integration.

Along with these, there has been the increased interest in development of multifunctional surfaces of implants that can respond both to regenerative needs and protective needs. Not only can these surfaces be useful in increasing bone formation but also they eliminate the chance of being colonized by harmful bacteria and also they have an effect on immune responses which decreases the chances of developing peri-implant complications. These novel forms of innovation are harbingers of a paradigm shift to the dynamic world of implant systems with dynamic interaction with the surrounding world. The increased rate of research development in the field demands a comprehensive evaluation of the current surface modification techniques and its applicability in the clinic. This review aims at clearly discussing the contemporary developments in the science of dental implant surface technologies and its effects on the process of as well as the mechanisms of action. There is a focus on bridging the scientific findings with the clinical realities in order to have a clear picture of the optimisation of surface engineering to enhance better-implant success.

2. Osseointegration Biological Background

The process of Osseointegration is regulated by a cascade of very coordinated biological events that begin immediately after the implant is placed until the end of the life of the implant. The initial step involves the rapid attachment of proteins present in blood and interstitial fluids onto the surface of the implant, creating a conditioning layer, resulting in further interaction of cells. The surface topography and chemistry influence the composition and structure of this layer of the protein and subsequently determine the cell adhesion and signaling pathways that are relevant to bone formation [9].

The character of the inflammatory response during the initial stages is a conclusive criterion that determines the success or failure of the process of osseointegration. Following the process of implantation, the cells of the immune system, including neutrophil cells and macrophage cells, are drawn to the area where they secrete cytokines and growth factors to shape the local microenvironment. An adequate ratio of the immune response will result in an extension of healing of the tissues when there is a proper balance of immune response and excess inflammation or time will lead to fibrous encapsulation instead of bone integration. Recent publications identify the role of immunomodulation in improving osseointegration specifically by the surface alterations which influence the polarization of macrophages and restrains the pro-inflammatory signaling [10].

The MSCs play a central role in the regenerative step of the osseointegration process in which they transform into osteoblasts which produce new bone. The recruitment, adhesion and differentiation of MSCs directly depend on the features of implant surfaces. Physical cues are provided by micro- and nano-scale surface features which replicate the exogenous

extracellular matrix of the bone leading to an increase in osteogenic differentiation and better mineral deposition. The cells receptors, the integrins, mediate interaction between cells and surfaces of the implant leading the cells to signal intracellular pathways that control cells and gene expression [11].

Bone remodeling is a continuous process of concerted action of osteoblasts and osteoclasts to keep the bone-implant interface constant. Surface properties vary this balance through the regulation of the cellular pathways through cellular activity and mechanotransduction. In such conditions as in osteoporosis when the bone resorption process is preeminent to the bone formation process, the surface structure of the implants is particularly important in the restoration of the balance and the osseointegration. It has been demonstrated through experiments that the optimized surface

properties can enhance bone development in even unfavorable biological conditions and this demonstrates the fact that surface engineering can be used to de-systemise systemic limitation [12]. The stage of formation of the first bone to the stability of bones over the long term involves the process of maturation and remodeling of new bone to the lamellar pattern structure that is able to withstand load functions. The presence of surface features which enhance early cellular response is also significant in achieving good long-term outcome since it results in enhanced anchorage of the bone and decreased micromotion at the interface. The combination of biological, mechanical and material factors has highlighted the complexity of the process of the osseointegration and the significance of surface design of the implants in order to include all steps of this process in Figure 1.

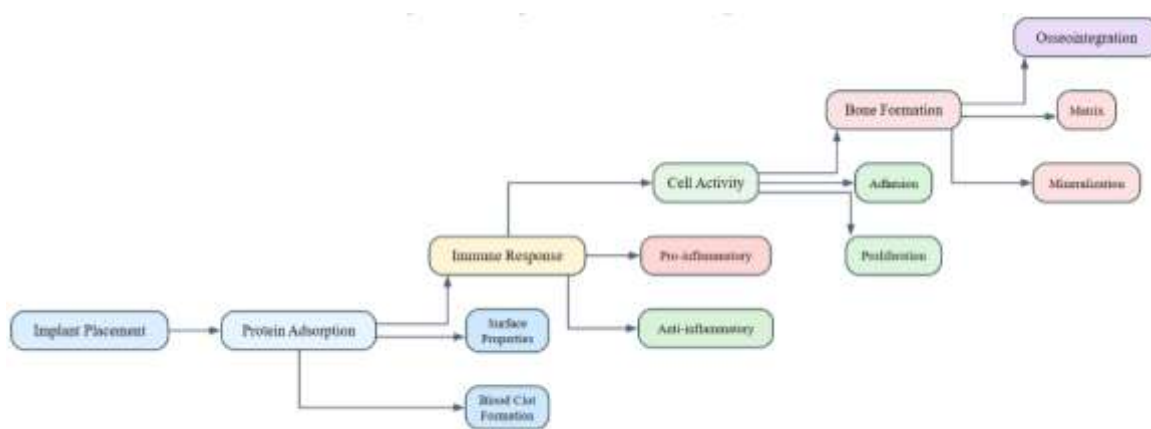


Figure 1: Key biological stages of osseointegration

In general, the biological nature of an osseointegration is considerably influenced by the properties of the implant surface that regulates the behavior of cells, immunity response as well as the bone remodeling dynamics. The understanding developed of these mechanisms is what makes it possible to develop high-performance surface technologies with the aim of enhancing clinical outcomes.

3. Improved Implant Surface technologies were categorized

Dental implant surface technologies are divided into types based on the nature of the type of modifications applied on the implant surface and generally into subtractive, additive and physicochemical. Subtractive methods involve removal of materials on the surface of implant to form micro-scale roughness that enhances the mechanical locking with the surrounding bone tissue. Some of the common methods include the sandblasting and acid etching to form irregular patterns on the surface to promote primary stability and early osseointegration through monotonizing bone to implant contact [13]. Additive surface modification techniques entail deposition of bioactive substances on the surface of the implant in order to make the implant biologically

effective. These are hydroxyapatite, calcium phosphate, and bioactive Glass coating, and they are comparable in mineral makeup with the natural bone. These types of coatings enhance the osteoconduction, which leads to the provision of a favorable substrate for attachment and growth of bone cells. Some other recent developments include nanostructured surfaces and biomolecules, which are active to stimulate the osteogenic pathways and have higher chances to integrate into the tissue [14]. Physicochemical modifications refer to those modifications that change the surface chemistry and energy, without necessarily changing the overall topography. Such techniques as plasma treatment, anodization and chemical functionalization can change the charge, the wettability and the oxide layer composition of the surface. These changes influence the adsorption of proteins as well as the interaction with the cells which assists in fostering improved responses to healing at the initial stages. Higher hydrophilicity e.g. has been associated with better protein binding and quicker cellular adherence, an issue that has been pertinent in terms of successful osseointegration [15]. Table 1 provides a summary of key strategies of implant surface modification, their mechanism as well as their biological effect.

Table 1: Classification of Implant Surface Modification Techniques

Surface Modification Type	Technique	Mechanism of Action	Surface Characteristics	Biological Effect	Advantages
Subtractive	Sandblasting	Mechanical abrasion removes surface material	Increased micro-roughness	Enhanced mechanical interlocking, improved primary stability	Simple, cost-effective
Subtractive	Acid etching (SLA)	Chemical dissolution creates micro-pits	Micro-scale roughness, increased surface area	Improved osteoblast attachment and BIC	Widely used, clinically proven
Additive	Hydroxyapatite coating	Deposition of bioactive calcium phosphate layer	Bioactive, osteoconductive surface	Accelerated bone apposition	Mimics natural bone
Additive	Bioactive glass coating	Ion release stimulates bone formation	Reactive, ion-releasing surface	Enhanced osteogenesis	Promotes mineralization
Physicochemical	Plasma treatment	Alters surface energy and introduces functional groups	Increased hydrophilicity	Improved protein adsorption and cell adhesion	Enhances early healing
Physicochemical	Anodization	Electrochemical oxide layer formation	Porous oxide layer, increased reactivity	Enhanced osseointegration	Controlled modification

Contemporary implant surfaces are more likely to be mixed and matched, in a bid to create hybrid systems, which would take on both the mechanical and biological advantages. Indicatively an example of a micro-rough surface can be further coated with nano-scale to enhance stability and biological activity or a chemical treatment. The reason behind such multifunctional surfaces is to address multiple clinical issues simultaneously and these include low quality of bone and slow healing. The implant surface technologies classification is an ordered method of comprehending the various methods that can be applied to enhance the performance of the implants. It also cites the disposition to increasingly complex and multifunctional designs that are bidirectional, trying to strike a middle ground between the best of both, mechanical anchorage and biological integrations. All these developments indicate the modern stage of the development of implantology towards more progressive and biologically reactive systems.

4. Alteration of the Surface Topography

The surface topography is a highly significant aspect of the implant behaviour that has impacts on the behaviour of the cells, tissue integration, and the success of the osseointegration. It has been previously established that micro-scale surface modification is a successful method of increased implant stability. Grit blasting and acid etching are some of the methods that are employed to cause rough surfaces and enhance mechanical interlocking with the bone and would result in enhanced primary stability and faster healing [16]. The technology of implants has also been developed further with the introduction of nano-scale features on the surface since now they have the ability to interact on a molecular

level. The effect of nanotubes and Nanopatterned Coatings on protein adsorption and cellular signaling is found on nanostructured surfaces. These characteristics are similar to the natural extracellular matrix of bone so as to trigger adhesion, proliferation, and differentiation of the osteoblasts to enable bone formation [17].

A combination of both micro and nano-scale hierarchical surface designs can provide synergistic improvements by meeting both mechanical and biological requirements. Micro-scale roughness offers good initial fixation whilst nano-scale features offer good cellular responses and integration. It has been observed that such hierarchal forms would significantly increase the interactions of bone on top of implants as well as accelerate the structure of bone assimilation compared to one-scaled adaptations [18]. The surface alteration techniques used by lasers offer high level of control over the topography of surfaces allowing the generation of extremely tailored patterning of the surface to give the most bio responses possible. The causes are due to the texturing of femtosecond laser which allows the fabric of extremely controlled micro- and nano scale features, to enhance the use of retention of the micro- and nano scale features in connection with the fabric against bacterial affection. There is great reproducibility of these techniques and flexibility of surface design [19].

The new advances in the field of laser technology have further enhanced the possibility of tailoring the implant surfaces in order to gain some clinical applications. The task parameters, such as laser intensity, pattern geometry, etc., can be adjusted to desired values to optimize surface characteristics to give improved mechanical stability as well as biological performance. These innovations indicate the significance of the

topography on the surface in the assessment of the success of the implant and the necessity of rigorous and controlled methods of alteration [20]. Table 2 elaborates

the correlation between the surface topographical characteristics and cellular reaction that determine the process of osseointegration.

Table 2: Surface Topography and Cellular Response

Surface Scale	Technique	Surface Features	Cellular Response	Bone-to-Implant Contact (BIC)	Key Outcome
Micro-scale	Sandblasting, acid etching	Roughened surface (1–10 μm)	Increased cell adhesion and proliferation	Moderate increase	Improved primary stability
Nano-scale	TiO ₂ nanotubes	Nanotubular structures (<100 nm)	Enhanced osteoblast differentiation	High increase	Faster osseointegration
Nano-scale	Nanopatterning	Ordered nano-features	Regulated protein adsorption	Improved BIC	Biomimetic response
Hierarchical	Micro + nano combination	Multi-scale roughness	Synergistic cellular activation	Highest BIC	Optimal bone integration
Laser-textured	Femtosecond laser	Controlled micro/nano patterns	Directed cell alignment	Significant increase	Precision surface control

5. Surface Chemistry Modifications

The mediation of the interaction between dental implants and the biological environment is surface chemistry, a paramount factor. Protein adsorption, cellular attachment and tissue integration are impacted by chemical modifications and are necessary to maximise the process of osseointegration. Surface composition and energy have been shown to enhance biological response in nano-engineered surfaces which stimulates osteogenic activity and increases the performance of implants [21]. At the molecular scale, these alterations regulate the shape and the orientation of adsorbed proteins including fibronectin and vitronectin that directly influence the adhesion activity of cells through the integrins. These adhesion proteins form the density and the distribution that determines the following cellular signaling cascades with the way of the participation of the pathways related to osteoblast differentiation and extracellular matrix deposition. Therefore, surface chemistry simply cannot be a mere passive presence but rather it is an active mediator of primary biological processes at the implant interface.

The surface chemistry of the surface can be altered by laser polishing and other related chemical treatment as well as the overall biocompatibility of the surface is increased. These processes reduce the surface contaminants that may be disastrous to biological interchanges like the hydrocarbons and plant residual in the manufacturing process. Such treatments increase surface energy and hence increase in uniform cell adsorption and spreading can be attained and more uniform. Hydrophilic surfaces facilitate rapid wetting of blood immediately upon implantation, and this is necessary to form a stable fibrin network, which will serve as a substrate of cell migration. Enhanced wettability functionality, made possible through said changes, has been associated with increased protein adsorption, increased cellular adhesion, which is essential at the early phases of the process of osseointegration [22]. Moreover, the chemical stability

of the oxide layers can be realized through laser-based alterations and degradation can be reduced with time depending on the time, contributing to the long-term work of bedside implants.

Plasma based surface treatments consist of numerous surface chemistry alterations such as making surface more hydrophilic and introducing functional groups such as hydroxyl group and carboxyl group (i.e., improving surface chemistry) and are highly used. Gas plasma modification alters surface of the implant at the molecular scale, without altering the bulk properties and, therefore, does not affect mechanical integrity of the implant, but improves the biological performance. Such functional groups enhance the affinity of protein binding and give good possibilities of binding osteoblast and proliferation. Plasma treated surfaces are also less susceptible to bacterial adherence because of a modified surface charge and energy and belong to an improved peri-implant health. This has been observed to increase significantly early healing reactions and result in accelerated osseointegration [23] in privilege experimental articles. As well, aging effects at the surface can be rejuvenated by plasma treatments, and they can also give it hydrophilicity, which can be lost in storage.

The further treatment of the material by means of anodization and plasma jet guarantees the improvement of the surface chemistry by producing thick oxide layers with superior bioactivity and corrosion resistance. They are deposits of oxide that habitually include titanium dioxide or other bioactive elements that cover those surfaces that result in greater reactivity and activity in the creation of apatite in the physiological fluids. Plasma jet treatments produce extremely reactive surfaces that increase the pace of exchange of ions and preferential bone formation of a high rate at the grade of an implant. The fine-tuning of the surface chemistry is made possible by the ability to fine-tune the various parameters including the voltage, treatment time and space of the atmosphere to establish the surface

chemistry as per the needs in particular clinical applications. These methods lead to highly reactive surfaces that enhance rapid bone formation and incorporation particularly in impaired biological

situations that would otherwise have slowed down the healing capabilities [24]. Figure 2 displays the surface chemistry modification strategies with biologic effects.

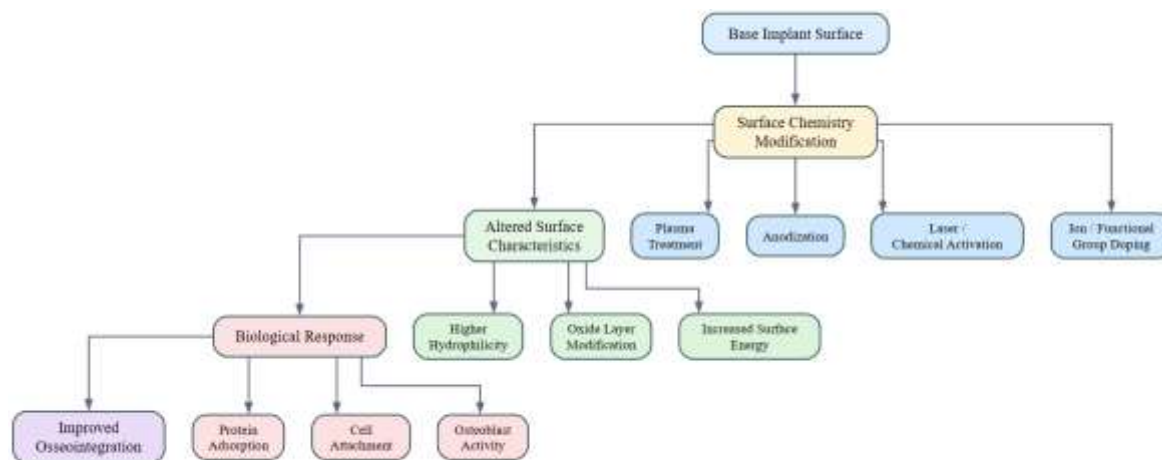


Figure 2: Surface chemistry modification pathways and effects

Besides such methods, a recent methodology of surface chemistry modification using ion doping and/or functional group grafting has also been formulated to enhance the biological performance further. Addition of elements like calcium, phosphorus, magnesium or strontium to the surface of the implants has been reported to cause osteogenic activity and increase in bone mineralization. These are significant in the metabolism of the bone and can be released to the correct extent so as to sustain remodelling activities. Likewise the chemical grafting onto the surface of bioactive molecules on the implant surface help induce a certain interaction with certain types of cells in order to induce better selective and efficient tissue integration. Altogether, the surface chemistry modifications are essential to design the implant surfaces which communicate with the biological environment. These changes increase the existence of enhanced protein adsorption, cellular signal pathway alteration, and selective systemic immune reaction to achieve therapeutic advantages of the implants in greater success in Osseointegration and prolonged functionality. The complex nature of chemical modification techniques combined with other surface engineering techniques is continually generating new designs of implants which have additional clinical outcome optimization possibilities.

6. Bioactive and functionalized Surfaces

The use of bioactive and functionalized implant surfaces is an astounding innovation in the field of dental implantology whereby the clinic is no longer interested in using a passive material but rather focusing on the biologically interactive system which can actively cause the body to respond by the promotion of the formation of bone. These surfaces will modify cellular behavior and giant, influence immune responses and reduce the colonization of microbes thereby increasing the short and long-term success of the implantation.

New materials such as MXenes have been of interest due to its capacity to counteract and interfere with the microbial membrane against antimicrobials with non-conventional antibiotics. These resources offer a viable solution to the decrease of biofilm formation on the implant surface, which is a top factor of the peri-implant infection and the implant failure [25]. Introduction into the implant coatings is a new method of introducing antimicrobial activity and biocompatibility. The extension of the functionality of the implants can also be done through immunomodulatory surface modification due to its impact on the host immune response. Altered polyetheretherketone (PEEK) surface have demonstrated to regulate the macrophage polarization and cause a shift in the pro-inflammatory phenotypes into the anti-inflammatory phenotypes, which is conducive to stimulating tissue regeneration. It is a regulated response of the immune system that is significant in the stable osseointegration particularly in patients with impaired healing [26].

The multifunctional surfaces are osteogenic, antibacterial surfaces that can be used to address multiple clinical problems simultaneously. Functionalization of carbon-fiber-reinforced PEEK implants, such as, has been done to facilitate bone growth and prevent bacteria colonization. Such dual functionality systems are particularly applicable to environments where there is an infection or high risk, and therefore, needs regeneration and protection [27]. Bioactive molecule surface coating such as allylamine has been discovered to enhance osteogenic differentiation and stimulation of bone formation. These types of coatings modify surface chemistry to increase cellular association and activate bone regeneration initiating signaling-pathways. The potentially successful aspect of the modification at a molecular level is indicated by such biofunctionalization strategies as the enhancing of implant integration [28]. A summary of bioactive and functionalized surface modification and

their applications in osteogenesis and infection control is provided in Table 3.

Table 3: Bioactive and Functionalized Surface Strategies

Modification Type	Material/Agent	Mechanism	Target Effect	Clinical Relevance	Limitations
Antimicrobial	MXenes	Disrupt bacterial membranes	Infection prevention	Reduces peri-implantitis risk	Long-term safety unclear
Immunomodulatory	Modified PEEK	Regulates macrophage polarization	Reduced inflammation	Improved healing in compromised patients	Limited clinical data
Multifunctional	Carbon-fiber PEEK	Combines antibacterial + osteogenic effects	Dual-function integration	Useful in infected environments	Complex fabrication
Osteogenic	Allylamine coating	Enhances osteoblast differentiation	Accelerated bone formation	Faster healing	Stability concerns
Bioactive	Bioactive glass	Releases Ca ²⁺ and Si ions	Stimulates mineralization	Improved integration	Brittle coatings

Furthermore, bioactive Glass coating have in fact demonstrated the capability of releasing ions that stimulates osteogenesis and enhance the responsiveness of cells. These are materials that participate in enhanced structural and functional integration by offering a favourable biochemical environment at the implant interface [29]. The overall bioactive and functionalised surfaces are a paradigm shift of implants design with the focus being on dynamic interactions with the biological environment. These are innovations that are intended to promote the result of the process of osseointegration and simultaneously treat infection control and immune control.

7. Manufacturing and Coation Technologies High-premier

The possibilities of dental implant surface engineering have been multiplied by advanced technologies of manufacturing and coating in the effort of controlling the surface features and material property in a more accurate manner. These technologies are able to generate complicated surface structure to enhance mechanical stability of the surface as well as biological functionality.

Surface modification technique using laser has widely been used due to its precision and versatility. The laser processing enables production of micro- and nano-sized patterns with controlled features that enables increased osseointegration through increased cellular attachment and bone growth. The added benefit of these techniques is that they can be reproducible, as well as, can tailor the surface characteristics to the specific clinical requirements [30].

The use of bioactive materials like hydroxyapatite on the surface of implants can be done by the method of

sol-gel coating. These surfaces are similar to the minerals make up of bone and also induce osteoconduction in which bone grows fast at the implant surface. The sol/gel process has homogenous deposit of coating and precise control of material composition [31]. Generally and 3D printing specifically, additive manufacturing has enabled the transformation of implant designs to produce customised implant with complicated geometries and regulated porosity. This technology provides the generation of surface changes into the structure of the implant in case of potential step-up in both mechanical and biological performances. The fact that it can be custom made implies that the impending implantology may make tremendous progress in the customization of implants as per the special anatomical and functional needs of a patient [32].

Processing parameters which influence the surface properties of additively manufactured implants include temperature, layer thickness and material composition. It is crucial that these parameters should be optimised to obtain desired surface properties that lead to stimulation of the surface to achieve the desired result of stimulating or promoting the occurrence of the process of osseointegration. Surface roughness and porosity are also critically essential in enhancing bone growth and stability [33]. The manufacturing capability is further enhanced by ultrafast laser technologies that allow creating highly accurate surface features of micro and nano-scale. These methods contribute to the creation of advanced implant surfaces of better biological activity and the decrease in the likelihood of complications [34]. The key methods of manufacture and coating are highlighted in Figure 3.

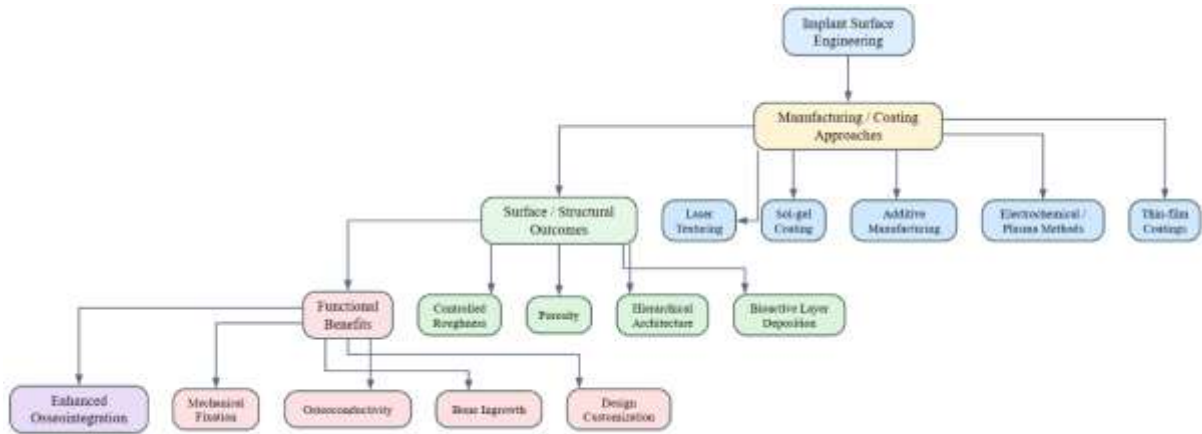


Figure 3: Advanced manufacturing and coating approaches

In sum, the high-technology manufacturing and coating tools are highly useful means of optimization of the surface of an implant that enables creating the next generation of implants.

8. Zirconia and Alternative Biomaterial.

Zirconia is shown to be a viable substitute to titanium in dental implantology considering that it possesses good aesthetics, anti-corrosive and biocompatible properties. Zirconia unlike titanium is a tooth-like color, and this will allow them to be used in the anterior part and aesthetics is the most important in this area. Design improvements over zirconia implants have been directed towards the enhancement of surface properties to enhance the level of osseointegration and mechanical behaviours [35].

Zirconia implants need to be modified on the surface to counter their rather inert nature. Methods have been used to augment surface roughness that promotes cellular adhesion including sandblasting, acid etching and doing with bioactive substances. These changes

have pro-osteoblast and pro-osteogenic effect that increases osseointegration [36].

Comparative analysis of titanium and zirconia implants has proved that there are differences in the mechanical and biological characteristics of the two materials. Although titanium possesses a high degree of mechanical strength in addition to long term clinical success, zirconia provides benefits in terms of aesthetics and fewer cumulation of plaque. These differences are important in the selection of materials that are suitable with regard to the clinical needs [37]. Both titanium implant and zirconia implant have hydroxyapatite coating to support their performance by an interface that is bioactive and helps in formation of bone. Such kinds of coating are composed of a similar minerals composition as the natural bone and capitate osteoconduction that enhances integration and stability [38]. Figure 4 provides the comparison of the modification of implant biomaterials.

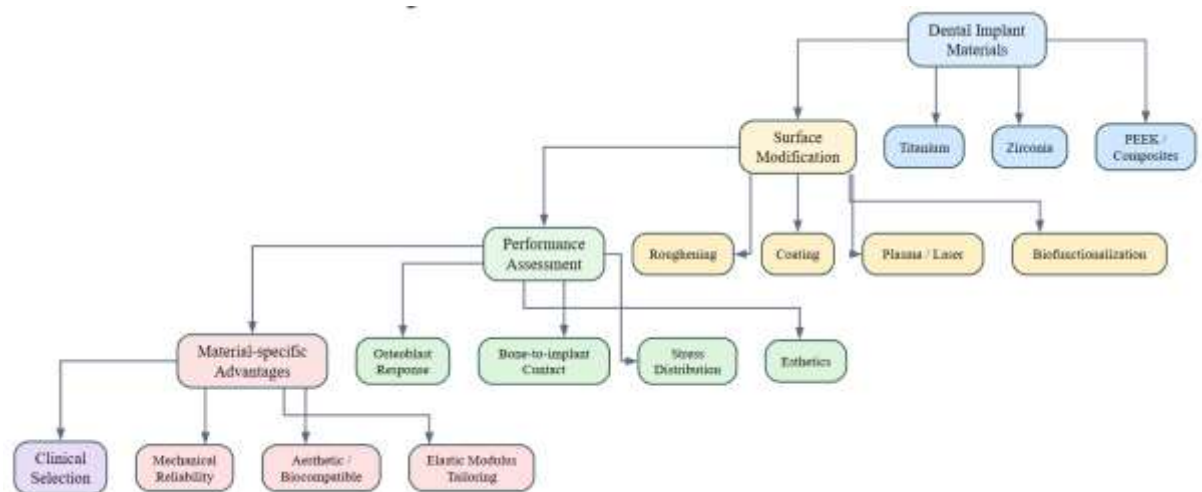


Figure 4: Comparison of implant biomaterials and modifications

PEEK and composite materials are other biomaterials that are being studied as proprietary implants in lieu of Zirconia. The benefits of these materials are that they have lower elastic modulus and enhance the stress

distribution that may decrease the bone resorption and improve the long term results. They however, require additional studies in their clinical use to ensure its reliability and effectiveness. In general, the zirconia

invention and the substitute biomaterials represent the next step of the further targeting of the improved functionalities of the implants with the relation to the mechanical and biological. The materials provide new opportunities of enhancing the process of osseointegration and provide novel options of treatment.

9. Surface Technologies Surface Technologies Evaluation

Dental implant surface technologies are important in evaluation to instill meaning on the biological performance and clinical applicability of the technologies. The efficacy of surface modifications and different surface modifications are assessed through a combination of in vitro, in vivo and clinical investigation.

Pre-clinical assessment requires the use of animal models where there is information on the biological responses in controlled settings. These models allow assessing the bone formation, implant stability, and tissue integration, and they provide valuable information regarding the functionality of modified

implant surfaces [39]. They are particularly used in the study of primary curing mechanisms and the mechanisms that make up the basis of osseointegration. The development of 3D printing has enabled the creation of implants with a custom surface structure that can be tested to determine the potential to enhance the process of osseointegration. Research has indicated that the 3D printed implants with optimized surface properties are more effective about bone development and mechanical stability compared to traditional implants [40]. The effect of surface changes on the nano-scale scale has been adequately tested on their influence on osseointegration. These researches have revealed that nanostructured surfaces offer enhanced cell reaction, increased bone-to-implant contact and accelerated healing. The effectiveness of these changes to enhance clinical outcome is supported using systematic assessments [41]. Table 4 summarizes the relevant preclinical and clinical evaluation methods which are applied in the assessment of the performance of implant surfaces.

Table 4: Evaluation Methods and Clinical Outcomes

Study Type	Evaluation Method	Parameter Measured	Outcome Indicator	Strengths
<i>In vitro</i>	Cell culture assays	Cell adhesion, proliferation	Biocompatibility	Controlled environment
<i>In vitro</i>	Protein adsorption studies	Protein binding kinetics	Surface reactivity	Mechanistic insight
<i>In vivo</i> (animal)	Histomorphometry	Bone-to-implant contact (BIC)	Osseointegration level	Biological relevance
<i>In vivo</i> (animal)	Removal torque test	Mechanical stability	Implant fixation strength	Quantitative
Clinical	Radiographic analysis	Marginal bone loss	Long-term success	Direct relevance
Clinical	Survival rate analysis	Implant success/failure	Clinical outcome	High reliability

All these evaluation approaches are combined to provide the complete picture of the performance of implant, which is able to develop the superior surface technologies. It is essential that the translation of the experimental outcomes into the field of practice should be accompanied by continued changes in the testing methodologies.

10. Antimicrobial /Peri-Implantitis

Peri-implantitis is among the greatest complications of dental implantology that is defined as inflammation and progressive destruction of bone because of the development of microbial biofilm. It is thus important to prevent the bacterial colonization of the surfaces of the implants in order to achieve long term success of implants.

Several surface modifications on the nano-scale have been engineered which prevent bacterial adhesion and biofilm formation. These methods use materials that are antibacterial in nature and interfere with the membranes of the microbes as a result, preventing their colonization. These strategies prevent the tendency of resistance to develop since the risk of infection is diminished without the adoption of the antibiotics [42]. It has been demonstrated that laser-polished surfaces of implants possess superior biocompatibility and reduced

adherence by bacteria. Laser polishing decreases the areas that bacteria can adhere and proliferate by creating the surface with less and nonspecific smoothness and uniform elements. Meanwhile, such surfaces guarantee decent cellular attachment and tissue integration [43]. Introduction of antimicrobial qualities on implant surfaces is a significant move towards discovery of solution to peri-implant diseases. These plans endeavor to achieve a balanced environment that favors the process of osseointegration but does not allow infection to occur [44]. In general, surface modification in antimicrobials is significant in improving the life and reducing the complications of the implant. Surface alterations by the use of antimicrobials are associated with long-term survival of implant, and necessity of incorporating the infection control measures in the design of implants [45].

11. Conclusion

The development of technologies of dental implantation on the surface of the teeth made a significant contribution to the sphere of implantology because this fact has made the process of the active integration of the implant in the bones more foreseeable and effective. The evolution of the conventional smooth surfaces into the complex micro-, nano- and chemically modified

surfaces is a step in the biologically active implant systems capable of interacting dynamically with the surrounding tissue. These inventions have not only resulted in the enhancement of the early cellular reactions, but also the increase of the bone formation rate and claim the credit of the stronger and firmer bone-implant interface. Surface topography and chemistry has emerged as one of the aspects influencing implant success through influence on protein adsorption and cellular adhesion as well as immune modulation. Nano-scale functionality and bioactive surfaces have enabled application of biomimetic surfaces to the close analogous of the natural environment of bone to amuse osteogenic activity. Moreover, the incorporation of antimicrobial and immunomodulatory effect addresses such critical issues as peri-implantitis and slow healing of compromised individuals. Advanced technologies of production like additive manufacturing Banko The and laser texturing have improved the probability to produce tailor-made implant surfaces with an ideal condition in structures and biological characteristics. Some further methods of better clinical results (at least in the case of aesthetic demanding or otherwise biologically challenging cases) are offered by the development of alternative biomaterials such as zirconia and functionalised polymers. Although these developments have been made, there remain challenges of putting down long-term stability, standardization of surface modifications and successful translation of the research done in the experimental research into the clinics. Future research ought to be done about designs and fabrications of multifunctional and customized surfaces of implants that possess the regenerative and antimicrobial and immunomodulatory properties. The enhancement of the relationships between implant surfaces and the biological environment is an improved understanding of which will be essential to the evolution of the implant technology and enhanced patient end results.

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