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Review Article

Enhancing osseointegration: A comprehensive review of UV photofunctionalization for titanium dental implants

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Abstract

Background: Osseointegration is crucial for dental implant success, and surface modifications of titanium implants have been explored to enhance their biological performance. Ultraviolet (UV) photofunctionalization has emerged as a promising method to improve the physicochemical and biological properties of titanium and titanium alloy implants. This review examines the mechanisms, effects, and clinical significance of UV photofunctionalization in oral implantology.

Materials and Methods: Literature was search for this narrative review was done using PubMed, Scopus, Web of Science, and Google Scholar. The search terms included "UV photofunctionalization," "titanium dental implants," "osseointegration," and "implant surface modification." Studies published between 2009 and 2023 were included, focusing on in vitro, animal, and clinical research on UV-treated titanium implants.

Results: UV photofunctionalization reverses the biological aging of titanium by removing hydrocarbon contamination, restoring hydrophilicity, and enhancing electrostatic properties. These modifications increase protein adsorption, improve osteoblast adhesion, and accelerate osseointegration. Studies have shown that UV-treated implants achieve nearly 100% bone-to-implant contact (BIC), improving primary stability and reducing healing time. Additionally, UV treatment may mitigate peri-implant diseases and enhance implant success in medically compromised patients.

Conclusion: While in vitro and animal studies strongly support UV photofunctionalization's benefits, clinical evidence remains limited. Standardization of treatment protocols and long-term clinical validation are needed to optimize its application in implantology

Keywords: UV photofunctionalization, Titanium implants, Osseointegration, Bone-to-implant contact, Dental implants, Surface modification.

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1. Introduction

Dental implant treatment has revolutionized modern dentistry, offering a reliable and effective solution for the replacement of missing teeth. Unlike traditional restorative options, dental implants provide a stable and durable foundation that mimics natural tooth function and aesthetics, significantly improving patients' quality of life. The success of implant therapy, however, is influenced by a multitude of factors ranging from surgical techniques to patient-specific variables. Among these factors, osseointegration remains the cornerstone for implant success.

According to GPT 10, Osseointegration (OI) is defined as the apparent direct attachment or connection of osseous tissue to an inert, alloplastic material without intervening fibrous connective tissue.[1] It is the direct structural and functional connection between the ordered living bone and the surface of a load-bearing implant at the histological level.[2] When this bone-implant contact occurs without the intervention of soft tissue between the bone and the implant surface, it results clinically in a long-term, rigid, and stable fixation of the implant within the surrounding bone.[3]

Titanium is the predominant material used for dental implant fixtures due to their biocompatibility, high resistance to corrosion, and high tensile strength, and this was reflected clinically in the high survival rates and long-term stability. Currently, six different variants of titanium are available as implant biomaterials. Among them, four are grades of

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commercially pure titanium (cpTi) (Grade I, Grade II, Grade III, and Grade IV), which is 98–99.6% pure titanium, and the remaining are titanium alloys (Ti-6Al-4V and Ti6Al-4V—Extra Low Interstitial alloys).[4] These grades are different in resistance to corrosion, strength, and ductility. The main alloy used is called commercially pure titanium cpTi. For both of the main alloys used to make implantable devices, namely commercially pure titanium, cpTi, and Ti-6A1-4V, the surfaces are mainly composed of the oxide Titanium Dioxide (TiO_2). This oxide layer is 4 – 6 nm thick and also contains hydroxyl groups in addition to the oxide. The exact composition of the surface is important in promoting the adhesion of osteoblasts and the oxide layer tends to have favourable biological properties. The oxide coating also has the effect of passivating the metal, so that corrosion is inhibited and the release of titanium ions is minimized. The surface of titanium (to be exact, TiO_2) has been considered chemically stable over time. However, titanium naturally loses some of its properties after being stored for a while. Biological aging of titanium is a spontaneous and inevitable process that begins immediately after the product's manufacture.[5] This phenomenon affects both smooth machine surfaces and acid-etched surfaces in an identical manner, without exception. Additionally, the aging process is typically completed within four weeks following production. As a result of aging, titanium surfaces become coated with hydrocarbons instead of titanium dioxide. Also, there have been concerns regarding implant material degradation, allergic reactions, and chronic peri-implant inflammation leading to failure and loss of implant. Alterations to the physico-chemical composition and/or modifications of the surface layer of implant materials are continuously being investigated to avoid failure of implants and performing reimplantation operations.

Various surface modification techniques have been explored to enhance the osseointegration and bioactivity of titanium implants. These include sandblasting and acid etching (SLA), anodization, plasma spraying, ion implantation, and chemical coatings. Each method offers distinct advantages; for instance, SLA enhances roughness and wettability, anodization increases oxide layer thickness for better bioactivity, and plasma spraying improves implant integration by depositing bioactive coatings like hydroxyapatite[6]. However, these techniques have limitations such as altered mechanical properties, potential contamination, and variable long-term stability. Compared to these methods, UV photofunctionalization (PhF) offers a unique advantage by directly reversing the biological aging of titanium surfaces without altering their microstructure. It enhances surface hydrophilicity, increases protein adsorption efficiency, and improves osteoblastic activity—achieving nearly 100% bone-to-implant contact (BIC), surpassing conventional methods.[3,5]

Despite significant progress in titanium surface modification, a comprehensive understanding of UV photofunctionalization's mechanisms, comparative advantages, and clinical implications remains necessary. This review aims to consolidate current evidence on UV PhF, analyse its superiority over conventional techniques, and highlight its clinical potential in enhancing implant success rates, particularly in medically compromised patients. Furthermore, it emphasizes the need for standardizing UV treatment protocols, evaluating long-term clinical outcomes, and integrating photofunctionalization with emerging implant technologies.

1.1. Biological aging

The term 'biological aging' is defined as the time related degradation of the physiochemical properties of the implant surface. The surface of titanium, particularly in the form of titanium dioxide, was long thought to be chemically stable over time. This assumption led to the belief that titanium's biological properties would remain consistent. However, recent research has shown that surface properties of titanium can change significantly over time. Detailed analysis using X-ray photoelectron microscopy revealed that the carbon content on titanium surfaces increases with time. Initially, acid-etched titanium surfaces had 14% carbon, but this grew to 63% after being stored for four weeks under ambient conditions.[7] This increase is due to the unavoidable deposition of atmospheric carbon onto the titanium in the form of hydrocarbons. Notably, the ability of titanium surfaces to attract proteins and osteogenic cells is strongly inversely related to the carbon percentage on the surface, suggesting that surface carbon significantly affects titanium's biological properties. Despite the inevitability of hydrocarbon deposition as a form of chemical contamination, future implant therapies should strive to keep titanium surfaces as clean as possible, following the principle that "the cleaner, the better".[8]

As a result of this, hydrophilicity of titanium surface will decrease with time. Recent studies have shown that titanium surfaces immediately after processing, regardless of the processing method, exhibit a water contact angle of 0^0 or less than 5^0. These surfaces are termed superhydrophilic, characterized by a contact angle of less than 5^0. This superhydrophilic property gradually diminishes, becoming hydrophobic within 2 weeks, with a contact angle exceeding 40^0. After 4 weeks, acid-etched surfaces display a contact angle of over 60^0.[8] Representative images of water droplets placed in variously aged titanium discs are presented (**Figure 1**)

The rate and capacity of protein absorption are crucial factors in determining the biocompatibility of any implantable materials or tissue engineering scaffolds.[9] With biological aging, protein absorption efficiency and capacity will get drastically reduced and will affect osseointegration. For successful osseointegration of dental implants, the quantity and quality of cell attachment on titanium surfaces are vital along with protein absorption. The number of osteogenic cells adhering to titanium can directly influence the volume of peri-implant bone formation. Improved cell spread and cytoskeletal development during the initial cell attachment to biomaterial surfaces ensure cell retention and the rapid initiation of cellular functions.[8] With aging, a decline in cell attachment was confirmed on titanium surfaces regardless of the type of microtopography.[10,11]

For achieving high quality bone-titanium integration, a well mineralized matrix must form around the implant surface. With increase in the storage time, osteogenic cell proliferation will get slow down and the rate of osteoblastic differentiation and mineralization will get affected. As a result, osteoconductivity will get decreased. As a result, long time will be taken for peri-implant osteogenesis and biomechanical strength of bone-implant integration will be compromised.[8] Thus, physiochemical and biological capabilities of the implant will get compromised.

1.2. UV photofunctionalization

UV photofunctionalization is defined as the treatment of titanium with intense UV light immediately before use and it will significantly increase the bioactivity of titanium in numerous ways. Light is categorized into different bands based on wavelength, including infrared (IR), visible light, and ultraviolet (UV). Among these, UV light has the shortest wavelength and the highest energy, making it highly reactive in modifying surface properties.

Characteristics of UV Light are as follows

1. Wavelength Range: UV light falls between 100–400 nm, subdivided into UVA (320–400 nm), UVB (290–320 nm), and UVC (100–290 nm). The range commonly used in biological research is 200-400 nm[13].
2. High Energy & Reactivity: UVA light has sufficient energy to break molecular bonds, making it effective for surface modification and decontamination.[13]
3. Photocatalytic Properties: UVC exposure activates titanium dioxide (TiO_2) surfaces, leading to enhanced hydrophilicity, removal of hydrocarbons, improving protein adsorption and cell functionality.[14]
4. Sterilization Effect: UVC light has potent antimicrobial effects, commonly used for disinfection in medical applications.[6]

UV Photofunctionalization alter the Titanium surfaces and enhance its physiochemical and biological capabilities. This process is a unique and straightforward mechanism that significantly boosts the biological capacity of titanium implants, achieving nearly 100% bone-to-implant contact or "Superosseointegration" compared to less than 55% for untreated implants.[15] Photofunctionalization enhances protein affinity to the implant surface, significantly improving physiological function and the expression of osteogenic cell phenotypes. This enhancement in biological integration is fundamentally driven by three changes to the titanium surface:[3]

1. PhF restores the lost hydrophilicity due to the biological aging of titanium, transforming the surface from hydrophobic to "Superhydrophilic."
2. It optimizes the electrostatic status of the surface, shifting it from an electronegative to the original electropositive state found on fresh titanium surfaces.
3. It removes a significant amount of hydrocarbon that inevitably accumulates on the surface over time.

Figure 2 shows the schematic comparison between the physiochemical properties of the titanium's surface as received "aged" and the titanium's surface following Photofunctionalization. Photofunctionalized surface shows much higher wettability across the implant surface than the non-treated surface.

The surface charge on the UV treated surface becomes positive, allowing the negatively charged osteoblasts and stem cells to attach alone or through serum proteins. The non-treated surface is negatively charged and the only method of cells to attach is via bridging divalent cations (Mg^{++}, Ca^{++}). Monovalent cations (Na^+ and K^+) competitively inhibit cell attachment. Photofuncionalization removes the hydrocarbon layer from the surface allowing for more protein absorption, and better attachment and spread of osteoblasts[3].

1.3. Mechanism

TiO_2 in any form exhibit excellent optical properties. Due to their chemical stability and high reactivity, they possess powerful photocatalysts. Fujishima and Honda suggested that the water molecules decomposed into oxygen and hydrogen with TiO_2 as a cathodic catalyst and in the presence of UV light, following the overall equations below:[6]

Oxidation reaction: $TiO_2 + h\nu \rightarrow e^- + h^+$ ……….. (1)

Reduction reaction: $2H_2O + 4h^+ \rightarrow O_2 + 4H^+$ ……..... (2)

$2H^+ + 2e^- \rightarrow H_2$ ……….. (3)

Overall reaction: $2H_2O + 4h\nu \rightarrow O_2 + 2H_2$ ……….. (4)

With long storage time, TiO_2 surface has been reported to gradually increase in the water-contact angle. But UV irradiation repeatedly regenerated the surface amphiphilicity by this water decomposition reaction. It is a photochemical reaction catalysed by TiO_2 upon exposure to UV light.

Certain molecules, such as oxygen and water, are adsorbed onto or desorbed from titanium surfaces when exposed to UV light with wavelengths shorter than titanium's band gap, approximately 415 nm, or with energy above the band gap energy.[13] The photo-induced superhydrophilicity of TiO_2 surfaces was initially attributed to an increase in hydroxyl groups formed through UV light irradiation. During UV exposure, photoexcited electrons are captured by oxygen molecules, creating holes and forming electron-deficient transition species. These species deprotonate water molecules, resulting in the formation of two hydroxyl groups, each coordinated to different titanium cations. This process creates surface oxygen vacancies at the bridging sites, converting Ti^{4+} sites to Ti^{3+} sites, which are favourable for dissociative water adsorption[14]. In the absence of light, the hydroxyl groups gradually desorb from the surface as H_2O_2 or $H_2O + O_2$.

Photocatalytic decomposition of organic contaminants differs from photoinduced hydrophilic conversion. When TiO_2 is exposed to UV light with wavelengths less than 380 nm (energy greater than TiO_2's band gap of 3.2 eV), it generates an electron-hole pair.[13] This process rapidly reduces and oxidizes adsorbed molecules such as oxygen and water, producing reactive oxygen species like superoxide ions ($•O_2^-$) and hydroxyl radicals (•OH). These radicals react with inorganic or organic surface impurities, leading to their decomposition and the removal of hydrocarbon compounds from the titanium surface. The overall reaction is schematically shown in **Figure 3**.

Greater carbon contamination is observed on non-UV-treated surfaces compared to UV-treated surfaces, with UV treatment reducing the carbon content. The removal of carbon increases wettability and changes the surface charge from electronegative to electropositive.

1.4. Procedure

For photofunctionalization, UV light exposure of implants can vary from 15 minutes to 48 hours. Various photodevices (**Figure 5**) are available. Duration of the exposure and usage depends on the photodevice. Recently introduced DIO-navi UV activator need only 20s while DENTIS SQ Activator claims only 10 seconds for UV activation of dental implants. With a Therabeam device (**Figure 5**B), 15 minutes of exposure is needed and is done immediately before placement of implant and the procedure is as follows. The dental implant can be placed on the stand table via an implant driver (**Figure 4**A). The table is then inserted into the device chamber, and the button to start UV irradiation is pressed. After 15 minutes of UV treatment, a 5-minute ozone cleaning treatment followed (**Figure 4**B), completing the photofunctionalization process. The chamber is then opened, and the photofunctionalized implant is carefully retrieved. It is then repositioned into the handpiece head with straight Pean forceps (**Figure 4**C). The dentist then carefully placed the photofunctionalized implant into the implantation socket, ensuring it do not come into contact with any other fluid, device, or tissue.[5] But here, there is a possibility of contamination of implant surface as immediately after opening the vial, implant surface can get contaminated. This problem is avoided in a DIO-navi system as here, implant is placed in the system for activation without opening the vial. The vial is opened only just before placement in the patient's mouth.

1.5. Effects of UV photofunctionalization

According to Elkhidir et al,[3] the effects of UV photofunctionalization can be categorized as physio-chemical, biological and Clinical effects.

Important physio-chemical effects are as follows:
1. Increase in the hydrophilicity of Titanium which favour better cell attachment.
2. Positively charged electrostatic surface which increases bioactivity and allows for direct protein-cell adhesion without the need for bridging molecules.
3. Hydrocarbon layer will be removed, thus, reversing biological ageing and allows for more cell attachment.

Important biological effects are as follows:
1. Increases efficiency and capacity of protein absorption.
2. Enhancement in osteoblastic attachment and spreading.
3. Enhancement in osteoblastic differentiation and mineralization.
4. Competitive reduction in bacterial biomass.

Important clinical effects are as follows:
1. Favour contact Osteogenesis.
2. Favour BIC from 55% to more than 98.2% (Super-osseointegration)
3. Stronger bone-implant integration, hence, better primary stability.
4. Faster osseointegration and reduced healing time.
5. Elimination of the 'Stability-dip'.
6. Less risk of bacterial infection.
7. Enhanced antibacterial effect.

Effects of UV photofunctinalization are summarized in **Figure 6**.

1.6. Clinical implications

Time-related biological degradation of Titanium surfaces adversely affect the osseointegration capacity and the healing process. Photofunctionalization reverses this healing process and result in Contact Osseogenesis and increase BIC. This leads to a three-fold increase in the strength of bone-implant integration. Thus, primary stability of implants will be increased. Both ISQ and Push-in values were higher in UV treated surfaces compared to aged titanium or new "as-received" titanium surfaces.[3] Load distribution will be better and the mechanical stress in the peri-implant marginal bone is reduced. The osseointegration process occurs four times faster and the average healing time required before functional loading reduces by one half compared to the non-photofunctionalized implants. Photofunctionalization enables a faster loading protocol and reduces the overall treatment time. It also allows the use of shorter and smaller-diameter implants without compromising the success rate. Thus, new treatment possibilities are opened for the use of these smaller implants in more complex cases with higher load or space requirements.

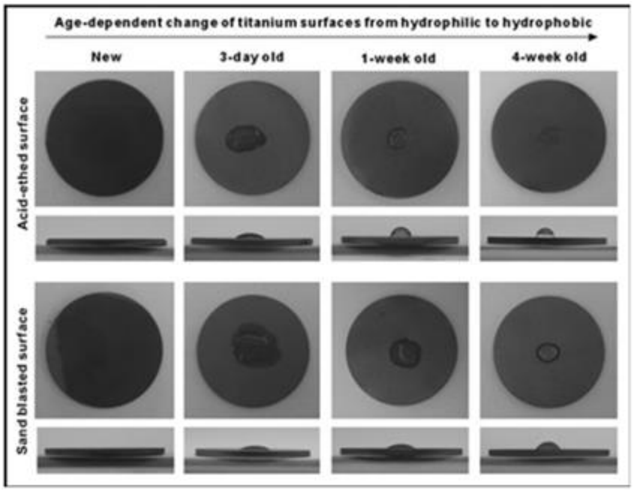

Figure 1: Time-dependent degradation of hydrophilic property on titanium discs. Top and side view images of 10 microL of water placed on acid-etched and sandblasted titanium discs with different age.8

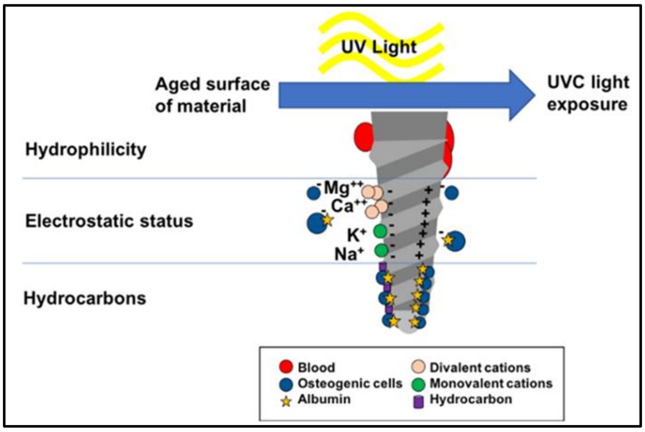

Figure 2: Schematic comparison between the physiochemical properties of the titanium's surface as received 'aged' and the titanium's surface following photo functionalization.[3]

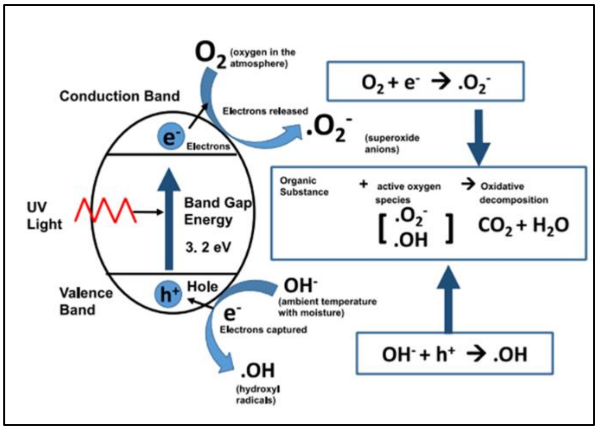

Figure 3: Schematic photoexcitation of an electron on the TiO_2 surface and the creation of holes, which attract water molecules to generate hydroxyl radicals and superoxide ions.[6]

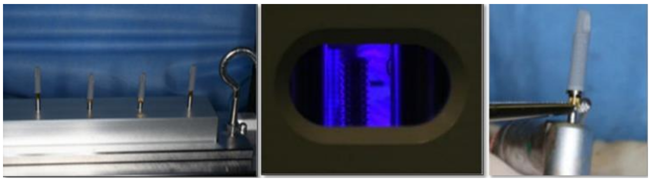

Figure 4: (**A**): Dental implant placed on the stand table: (**B**): UV treatment: (**C**): Repositioning into the handpiece head with straight Pean forceps.

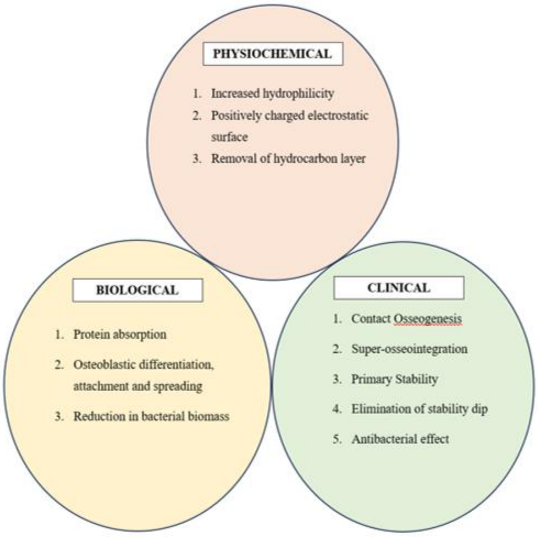

Figure 5: (**A**): DIO-navi UV Activator. (**B**): Therabeam UV Activator. (**C**): DENTIS SQ UV Activator (SQUVA)

Figure 6: Effects of UV Photofunctionalization

Table 1: UV Photofunctionalization- summary

Economic aspects	Logistical aspects	Practical aspects
Device Cost: UV photofunctionalization devices, such as the TheraBeam® Affiny, are commercially available and are considered relatively affordable compared to other advanced dental equipment. While exact pricing varies, they are generally within reach for many dental practices.	**Treatment Duration**: UV photofunctionalization is performed immediately prior to implantation, typically requiring about 15 minutes of UV exposure.	**Ease of Use**: The procedure is simple and can be performed chairside, requiring minimal training for dental professionals.
Cost-Effectiveness: The procedure is simple and low in cost, making it a cost-effective method to enhance implant therapy.	**Device Capacity**: The TheraBeam® Affiny can accommodate up to six implants simultaneously, enhancing workflow efficiency in clinical settings.	**Clinical Benefits**: UV photofunctionalization has been shown to enhance osseointegration, potentially allowing for faster loading protocols and improved implant stability.
	Integration into Clinical Workflow: The process is straightforward and can be seamlessly integrated into the existing clinical workflow without significant alterations.	

Other technologies can be incorporated successfully with UV Photofunctionalization. Advancements in nanotechnology such as ion beam deposition, nanoparticle compaction, acid etching, anodising, peroxidation, or chemical conjugation of biomolecules enhance osteoblastic behaviour and responses, improve cell adhesion properties and lead to rapid bone healing. Combining UV photofunctionalization with nanoscale topographies has demonstrated a synergistic benefit. For example, treatments such as fluoride application or microarc oxidation (MAO) on implant surfaces alone have been shown to improve cellular response and bone formation around the implant. However, incorporating UV light into the process further enhances cellular bioactivity and human mesenchymal stem cells (hMSCs) attachment to the implant surface, resulting in stronger and more accelerated osseointegration[3].

2. Discussion

The core principle of photofunctionalization is to cleanse titanium surfaces, which naturally become contaminated with hydrocarbons over time, thereby optimizing their ability to achieve osseointegration regardless of surface properties. This process reduces carbon accumulation on aged titanium surfaces to less than 20%, revealing the original titanium dioxide layer. This leads to a significant increase in osteoblast attachment on photofunctionalized titanium surfaces, resulting in rigid bone integration with nearly 100% BIC.[5]

Clinically, it has been reported that even with initial bone support of less than 25% of the implant length or an implant stability quotient (ISQ) of less than 30, photofunctionalization can achieve secure secondary stability. This indicates that photofunctionalization can overcome extremely low initial stability and/or limited bone support. The reason photofunctionalized implants achieve secure secondary stability, even with low initial stability, is due to their faster and effective osseointegration compared to untreated implants. Photofunctionalization prevents the temporary decrease in implant stability, known as the "stability dip," during the healing process.

The key aspects of osseointegration on photofunctionalized titanium surfaces include superhydrophilicity, absence of carbon contamination, and a positively charged electrical status[6]. Superhydrophilic surfaces effectively attract blood, supporting osseointegration, and positively charged surfaces promote rigid osteoblast attachment since osteoblasts are negatively charged.[16] Additionally, photofunctionalization significantly reduces bacterial contamination and biofilm formation on aged titanium surfaces. Hydrophobicity drives bacterial adhesion, so converting surfaces from hydrophobic to superhydrophilic via photofunctionalization provides an antibacterial effect. Photofunctionalization can also restore osseointegration in patients with type 2 diabetes.[17]

Photofunctionalization also reduces the production of reactive oxygen species (ROS), which can induce cell apoptosis, thereby enhancing osteoblastic activity on titanium surfaces.[18] This positive effect on bone healing was demonstrated using a gap-healing model that simulates insertion into an extraction socket.[19] In this model, photofunctionalized implants effectively attracted new bone formation into the gap. It indicates that the titanium surface can recruit and retain more osteogenic cells for contact osteogenesis.[20]

Furthermore, in an augmentation model using titanium mesh, the exposed part of the photofunctionalized implant attracted blood during surgery and was eventually covered with bone tissue. This suggests that the photofunctionalized implant acted as a guide for bone regeneration.[20] The rapid and strong osseointegration, coupled with the improved bone-healing mechanisms on photofunctionalized implant surfaces, can support the establishment of osseointegration in patients with severely compromised bone conditions. Therefore, photofunctionalization could be a valuable tool for ensuring secure osseointegration when implants are placed with simultaneous bone augmentation.[5]

Caroline et al[21] found that photofunctionalization alters the physicochemical properties of titanium and, when combined with biofunctional titanium-treated surfaces, enhances protein adsorption and reduces initial bacterial colonization without causing cytotoxic effects on HGF cells. Clinically, UV-mediated photofunctionalization of the titanium biofunctional coating is a promising approach to improving implant-host interactions and reducing oral biofilm-related diseases.

This comprehensive literature review has critically examined the current state of knowledge regarding UV photofunctionalization of titanium and titanium alloy dental implants. The collective body of evidence from in vitro studies, animal experiments, and limited clinical trials suggests that UV treatment holds significant promise for enhancing the bioactivity and osseointegration properties of dental implants.

The primary mechanism of UV photofunctionalization involves the alteration of the titanium surface at the atomic level. UV irradiation has been shown to remove hydrocarbons and other organic contaminants from the implant surface, resulting in a superhydrophilic state. This change in surface chemistry leads to enhanced protein adsorption, improved cell attachment, and accelerated osteoblast differentiation.

Several key findings have emerged from this review

1. Surface Characteristics: UV treatment consistently produces a more hydrophilic surface, with water contact angles approaching 0°. This superhydrophilicity is associated with increased surface energy and improved wettability, factors crucial for initial protein adsorption and cell adhesion.
2. Biological Response: In vitro studies have demonstrated enhanced attachment, spreading, and proliferation of osteoblasts on UV-treated surfaces. Additionally, increased expression of osteogenesis-related genes and higher levels of alkaline phosphatase activity have been observed, indicating improved osteoblast differentiation.
3. Osseointegration: Animal studies have shown faster and stronger bone-implant contact in UV-treated implants compared to untreated controls. Histomorphometric analyses reveal higher bone-to-implant contact percentages and greater bone volume around UV-treated implants.
4. Clinical Outcomes: Limited clinical studies have reported improved implant stability quotients, faster healing times, and higher success rates for UV-treated implants, particularly in challenging cases such as immediate loading protocols or patients with compromised bone quality.
5. Long-term Effects: Some studies suggest that the benefits of UV photofunctionalization may persist for extended periods, potentially improving the long-term stability and success of dental implants.
6. Combination with Other Techniques: Promising results have been observed when combining UV treatment with other surface modification techniques, such as sandblasting and acid-etching, indicating potential synergistic effects.

Table 1 summarizes the economical, logistical and practical aspects of UV photofunctionalization.

Despite the promising biological and clinical implications of UV photofunctionalization, several limitations of this review should be acknowledged. First, most of the included studies are based on small-scale animal models or in vitro experiments, which limits the direct applicability of findings to human clinical practice. Second, the review may reflect publication bias, as studies with favourable outcomes are overrepresented, while contradictory or null results are scarcely reported. Third, the variability in UV treatment protocols, surface types, evaluation periods, and outcome measures among studies introduces heterogeneity that complicates direct comparison. Moreover, the absence of long-term human trials restricts our understanding of the sustained effects and practical feasibility of UV-treated implants. Finally, the review lacks a detailed analysis of economic considerations and clinical integration challenges, which are crucial for real-world application.

3. Conclusion

UV photofunctionalization holds immense promise for revolutionizing dental implant therapy by improving outcomes, addressing biological challenges, and setting a new benchmark in implant success. Its widespread adoption has the potential to elevate the standard of care in dental implantology, ensuring more predictable and durable results for patients worldwide. As this field evolves, future research should focus on standardizing UV treatment protocols, understanding its effects on different implant materials, and exploring its compatibility with advanced implant designs. Additionally, integrating UV photofunctionalization with other emerging technologies, such as bioactive coatings and smart implants, may further enhance its clinical efficacy.

4. Source of Funding

None.

5. Conflict of Interest

None.

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