Open Access Library Journal
2025, Volume 12, e12383
ISSN Online: 2333-9721
ISSN Print: 2333-9705

Hydroxyapatite-Coated Titanium Dental Implants

Omar Ziyati[1], Salma Abou-Obeida[2], Ziad Walim[3], Khalid El Boussiri[4]

[1]Faculty of Dental Medicine of Casablanca, Periodontology Department, Hassan II University of Casablanca, Casablanca, Morocco
[2]Faculty of Dentistry, Dnepropetrovsk State Medical University, Dnipro, Ukraine
[3]Faculty of Dental Medicine of Casablanca, Mohammed VI University of Sciences and Health, Casablanca, Morocco
[4]Faculty of Dental Medicine of Casablanca, Fundamental Biomaterials Department, Hassan II University of Casablanca, Casablanca, Morocco
Email: elboussirik@hotmail.com

How to cite this paper: Ziyati, O., Abou-Obeida, S., Walim, Z. and El Boussiri, K. (2025) Hydroxyapatite-Coated Titanium Dental Implants. *Open Access Library Journal*, **12**: e12383.
https://doi.org/10.4236/oalib.1112383

Received: September 27, 2024
Accepted: April 25, 2025
Published: April 28, 2025

Abstract

Introduction: The use of titanium implants coated with hydroxyapatite (HA) in dental implantology represents a major breakthrough in dentistry, offering durable solutions for replacing missing teeth. The improved biocompatibility and osteointegration of these implants compared to pure titanium implants are examined in this study. Materials and Methods: A literature review was conducted using the PubMed and Google Scholar search engines, using specific keywords: Hydroxyapatite, Dental Implants, Titanium, Clinical Performances as well as Boolean equations to select relevant studies. In order to ensure the relevance and quality of the data analyzed, inclusion and exclusion criteria have been established. Results: Compared to pure titanium implants, HA-coated implants offer better osteointegration and biocompatibility. Included studies have demonstrated faster bone healing and reduced risks of postoperative complications, highlighting the effectiveness of hydroxyapatite as a coating for dental implants. Discussion: Clinical performance of dental implants is significantly improved by the use of HA as coating for titanium implants. However, further research is needed to assess the long-term impact on patient health and optimize coating processes. Conclusion: Hydroxyapatite-coated titanium dental implants offer considerable benefits in terms of osseointegration and biocompatibility, making them a major innovation in dental implantology. This review emphasizes the need for further research to maximize clinical use of these implants.

Subject Areas

Dentistry

Keywords

Hydroxyapatite, Dental Implants, Titanium, Clinical Performances

1. Introduction

Implantology has revolutionized the field of dentistry, providing an effective and permanent solution to replacing missing teeth.

Dental implants are titanium or zirconium oxide devices surgically inserted into the jawbone to replace the roots of natural teeth. They provide a solid foundation for bridges, crowns and complete dentures. These devices offer a more natural feel and greater stability than removable dentures. They also maintain the integrity of the jaw by stimulating bone growth and preventing bone resorption. Dental implants can be designed to perfectly match the color, shape and size of natural teeth.

This therapeutic solution is aimed at a wide range of patients, including edentulous people, people suffering from the loss of one or more teeth and those who wish to replace traditional prostheses with more modern, stable and comfortable implants.

The use of cone beam computed tomography (**CBCT**) for precise implant planning, computer-assisted surgery for minimal and precise interventions and the use of high-quality biocompatible materials for optimal bone integration.

Today, hydroxyapatite-coated dental implants are widely used in clinical practice and provide patients with predictable and long-lasting results. With continued advancements in materials research and technology, it is likely that the use of hydroxyapatite-coated titanium in dental implantology will continue to increase, providing new opportunities to improve clinical outcomes and quality of life for patients.

The present work aims to study the nanostructure of titanium implants coated with hydroxyapatite, their clinical performance, as well as to compare them with conventional dental implants.

2. Materials and Methods

2.1. Identifying the Literature

To meet the objectives of our subject, two types of search strategies documentary have been summer used for this literature review.

2.2. Digital Research Strategy

First of all, this involves research using computer databases accessible via the Internet. We examined PubMed, which provides access to the MEDLINE bibliographic database. Other search engines examined: Google Scholar.

We used the keywords (Dental Implants, Titanium, Hydroxyapatite, **Coating, Clinical Performance) to achieve targeted** and precise research.

These terms were used in each database searched separately and cross-referenced to identify articles for analysis after inclusion.

- *Boolean equations*:

  - Dental Implants and Hydroxyapatite

- Dental Implants and Coating
- Dental Implants and Hydroxyapatite and Coating and Titanium and Clinical Performances
- Hydroxyapatite and Titanium
- Hydroxyapatite and Coating

2.3. Bottom-Up Approach

This search strategy gave us the opportunity to collect from the already pre-selected reference list a number of articles that would have gone unnoticed in electronic research of interest to our topic.

2.4. Inclusion Criteria

We admitted during our bibliographical research:

- Articles meeting the objectives of our research.
- Articles with a publication date between 2014 and 2024.
- Articles published in English.

2.5. Exclusion Criteria

We have eliminated and excluded any criterion opposing this selection.

3. Results (See Table 1)

Table 1. Representative table of selected articles.

Title of article	Authors	Year	Bibliographic reference
Investigations of titanium implants covered with hydroxyapatite layers	B. Świeczko-Żurek, M. Bartmański	2016	[1]
Bioactive Surfaces vs. Conventional Surfaces in Titanium Dental Implants: A Comparative Systematic Review	Nansi López-Valverde, Javier Flores-Fraile, Juan Manuel Ramírez, Bruno Macedo de Sousa, Silvia Herrero-Hernández Antonio López-Valverde	2020	[2]
A Review of Hydroxapatite and Its Use as a Coating in Dental Implants	Joo L. Ong & Daniel CN Chan	2017	[3]
A short view on nanohydroxyapatite as coating of dental implants	Javad Yazdani, Elham Ahmadian, Simin Sharifi, Shahriar Shahi, Solmaz Maleki Dizaj	2018	[4]
Clinical Outcome of Hydroxyapatite Coated, Bioactive Glass Coated, and Machined Ti6Al4V Threaded Dental Implant in Human Jaws: A short-term comparative study	Surajit Mistry, Rajiv Roy, Biswanath Kundu, Someswar Datta, Manoj Kuma, Abhijit Chanda, and Debabrata Kundu	2016	[5]
Retrospective clinical outcome of nanopolymorphic crystalline hydroxyapatite-coated and anodic oxidized titanium implants for 10 years	Eiji Kato, Masahiro Yamada, Kaoru Sakurai	2014	[6]
Hydroxyapatite and Fluorapatite in Conservative Dentistry and Oral Implantology—A Review	Kamil Pajor, Lukasz Pajchel and Joanna Kolmas	2019	[7]

Continued

Efficacy of Nano-Hydroxyapatite Coating On Osseointegration of Early Loaded Dental Implants	Osama Alabed Mela, Mohamed Abdel-Monem Tawfik, Wael Mohamed Ahmed Said Ahmed, Fakhreldin Hassan Abdel-Rahma	2022	[8]
Surface modifications of endosseous dental implants by incorporation of roughness and hydroxyapatite coatings	Fahd Ahmed, Haroon Rashid, Sadaf Farookhi, Vivek Verma, Yuliya Mulyar, Murai Khalifa, Zeeshan Sheikh	2015	[9]
The Influence of Nanostructured Hydroxyapatite Surface in the Early Stages of Osseointegration: A Multiparameter Animal Study in Low-Density Bone	Suelen Cristina Sartoretto, Jose Calasans -Maia, Rodrigo Resende, Eduardo Câmara, Bruna Ghiraldini, Fabio Jose Barbosa Bezerra, Jose Mauro Granjeiro, Monica Diuana Calasans-Maia	2016	[10]
The Soft Tissue Immunologic Response to Hydroxyapatite-Coated Transmucosal Implant Surfaces: A Study in Humans	Elisabeth AWJ De Wilde; Ryo Jimbo; Ann Wennerberg, Yoshihito Naito; Paul Coucke; Matthew S. Bryington; Stefan Vandeweghe; Hugo De Bruyn,	2014	[11]
The biocompatibility of silver and hydroxyapatite coatings on titanium dental implants with human primary osteoblast cells	Ranj Nadhim Salaie, Alexandros Besinis, Huirong Le, Christopher Tredwin, Richard D. Handy	2019	[12]
In vivo biofunctionalization of titanium patient specific implants with nano hydroxyapatite and other nano calcium phosphate coatings: A systematic review	Alexander Bral, Maurice Y. Mommaerts	2022	[13]
In vitro assessment of the biological response of Ti6Al4V implants coated with hydroxyapatite microdomains	Salvador Clavell, Martín de Llano, Carda; Gómez Ribelles, Vallés-Lluch	2015	[14]
Systematic Review of Current Dental Implant Coating Materials and Novels Coating Techniques	Maria Xuereb, Josette Camilleri, Nikolai J. Attard,	2020	[15]
Effect of Induced Periimplantationitis on Dental Implants with and Without Ultrathin Hydroxyapatite Coating	Marwa Madi, Osama Zakaria, Shizuko Ichinose, and Shohei Kasugai	2019	[16]
Hydroxyapatite coating techniques for Titanium Dental Implants—an overview	Arati Sharma, BPKoirala	2015	[17]
Effects of a hydroxyapatite coating on the stability of endosseous implants in rabbit tibiae	Magdalena Łukaszewska-Kuska, Piotr Krawczyk, Agnieszka Martyla, Wiesław Hędzelek, Barbara Dorocka-Bobkowska	2016	[18]
Bio-implant as a novel tooth restoration loss	Dong-Joon Lee, Jong-Min Lee, Eun-Jung Kim, Takashi Takata, Yoshihiro Abiko, Teruo Okano, David W. Green, Masaki Shimono & Han-Sung Jung	2015	[19]
Combined antibacterial and osteogenic in situ effects of a bifunctional titanium alloy with nanoscale hydroxyapatite coating	Hua-Wei Liu, Dai-Xu Wei, Jiu-Zheng Deng, Jian-Jin Zhu, Kai Xu, Wen-Hao Hu, Song-Hua Xiao & Yong-Gang Zhou	2015	[20]
Microstructure and Wear Behavior of Ti Reinforced HVOF Coating	Szabo, ID Utu, I Hulka, l Bordeasu and I Mitelea	2023	[21]

Continued

Surface characterization and osteoblast response to a functionally graded hydroxyapatite/ fluorohydroxyapatite/titanium oxide coating on titanium surface by sol–gel method	G. He, B. Guo, H. Wang, C. Liang, L. Ye, Y. Lin and X. Cai	2019	[22]
Immediate and early loading of hydrothermally treated, hydroxyapatitecoated dental implants: a 7-year prospective randomized clinical study	A. Arghami, D. Simmons, J. St. Germain and P. Maney	2017	[23]
Randomized controlled clinical trial of 2 types of hydroxyapatitecoated implants on moderate periodontitis patients	Hyun-Suk Kim, Pil-Young Yun, Young-Kyun Kim	2018	[24]
Preparation of Bone-Implants by Coating Hydroxyapatite Nanoparticles on Self- formed Titanium Dioxide Thin-Layers on Titanium Metal Surface	WPSL Wijesinghe, MMMGPG Mantilaka, KG Chathuranga Senarathna, HMTU Herath, TN Premachandra, CSK Ranasinghe, RPVJ Rajapakse, RMG Rajapakse, Mohan Edirisinghe, S. Mahalinga	2018	[25]
Production of hydroxyapatite layers on the plasma electrolytically oxidized surface of titanium alloys	Alex Lugovskoy, Svetlana Lugovskoy	2014	[26]
Nanoporous hydroxyapatite/sodium titanate bilayer on titanium implants for improved osteointegration	A. Carradò, F. Perrin-Schmitt, QV Le, M. Giraudel, C. Fischer, G. Koenigb, L. Jacominec, L. Behr, A. Chalome, L. Fiettee, A. Morlet, G. Pourroy	2016	[27]
Taking Hydroxyapatite-Coated Titanium Implants Two Steps Forward: Surface Modification Using Graphene Mesolayers and a Hydroxyapatite-Reinforced Polymeric Scaffold	AM Fathi, MK Ahmed, M. Afifi, AA Menazea, and Vuk Uskokovic	2020	[28]
comparative study of zinc, magnesium, strontiumincorporated hydroxyapatite-coated titanium implants for osseointegration of osteopenic rats	Zhou-Shan Tao, Wan-Shu Zhou, Xing-Wen He, Wei Liu, Bing-Li Bai, Qiang Zhou, Zheng-Liang Huang, Kai-kai Tu, Hang Li, Tao Sun, Yang-Xun Lv, Wei Cui, Lei Yang	2016	[29]
Titanium Dental Implants: An Overview of Applied Nanobiotechnology to Improve Biocompatibility and Prevent Infections	Rayane CS Silva, Almerinda Agrelli, Audrey N. Andrade, Carina L. Mendes-Marques, Isabel RS Arruda, Luzia RL Santos, Niedja F. Vasconcelos and Giovanna Machado	2022	[30]
Bioactivity and Mechanical Properties of Hydroxyapatite on Ti6Al4V and Si (100) Surfaces by Pulsed Laser Deposition	Salizhan Kylychbekov, Yaran Allamyradov, Zikrulloh Khuzhakulov, Inomjon Majidov Simran Banga, Justice ben Yosef, Liviu Duta and Ali Oguz Er	2023	[31]
Effect of Er: YAG Pulsed Laser-Deposited Hydroxyapatite Film on Titanium Implants on M2 Macrophage Polarization In Vitro and Osteogenesis In Vivo	Lin Ma, Min Li, Satoshi Komasa, Shigeki Hontsu, Yoshiya Hashimoto, Joji Okazaki and Kenji Maekawa	2023	[32]
Vapor-Induced Pore-Forming Atmospheric -Plasma- Sprayed Zinc-, Strontium-, and Magnesium-Doped Hydroxyapatite Coatings on Titanium Implants Enhance New Bone Formation—An In Vivo and In Vitro Investigation	Hsin-Han Hou, Bor-Shiunn Lee, Yu -Cheng Liu, Yi-Ping Wang, Wei-Ting Kuo, I-Hui Chen, Ai-Chia He, Chern-Hsiung Lai, Kuo-Lun Tung and Yi-Wen Chen	2023	[33]

4. Discussion

4.1. Titanium and Its Alloys

Titanium, the ninth most common metal, was discovered by William Gregor in 1791. Low density (4.506g/cm^3) and high strength (590 MPa) are some of the characteristic physical and chemical properties of the silver metal in its form pure. Titanium and its biocompatibility are obtained thanks to the oxide layer present on its surface. Under ambient conditions, TiO_2 occurs in three crystalline forms:

- Rutile;
- Brookite;
- Anatase.

At the end of the synthesis, a heat treatment allows phase transitions. Brookite, arranged in an orthorhombic geometry, is the most difficult phase to obtain, while rutile and anatase are easily formed. The distortions between the octahedron formed by TiO_6 are the reason why the rutile and anatase phases differ. Various techniques ranging from hydrothermal to electrochemical techniques are employed to create these structures. Therefore, the preferential formation of one of the predicted phases is caused by changes in the physicochemical parameters of the synthesis. Titanium and its alloys are considered non-toxic and even more biocompatible than cobalt-chromium and stainless steel in the dental industry. They are also compatible with CT and MRI scans and are used to make dentures and implants [30].

Titanium alloys have the following properties:

- Low elastic modulus,
- Thin,
- Biotolerance,
- Good corrosion resistance,
- Paramagnetic properties,
- High strength
- Strong tendency towards self-passivation.

Ti-6Al-4V is a titanium alloy commonly used for endoprosthesis, though its long-term use may release toxic elements, which will be deposited in the brain and cause cancerous reactions. To adress this, new alloys were developed that did not contain the toxic elements mentioned above and enhanced biocompatibility. These alloys exhibit a lower elastic modulus than other metallic biomaterials, though still higher than the elastic modulus of the bone, enhancing implant resistance to stress and bone tissue regeneration. Anatase is often associated with applications requiring osseointegration and is therefore most commonly used in dental implants [1] [30].

Titanium is currently the most widely used material for manufacturing dental implants, although ceramics and polymers are also available. There are six types of titanium for implants: four grades of commercially pure titanium (CPTi) with a purity of 98 to 99.6%, and two alloys (Ti-6Al-4V and Ti-6Al4V-Extra Low Interstitial alloys) with very weak interstitials. These categories are distinguished by their ductility, strength and corrosion resistance, linked to residual oxygen in the metal. CpTi Grade IV, with an oxygen content of 0.4%, is most commonly used for its mechanical strength [30].

4.2. Hydroxyapatite and Its Applications in Dental Implantology

4.2.1. Structure of Hydroxyapatite

Hydroxyapatite (HA) **(Figure 1)** is a mineral form of natural calcium apatite with the formula $Ca_5(PO_4)_3(OH)$.

$Ca_{10}(PO_4)_6(OH)_2$ is usually written to indicate that the crystal unit cell includes two elements [4].

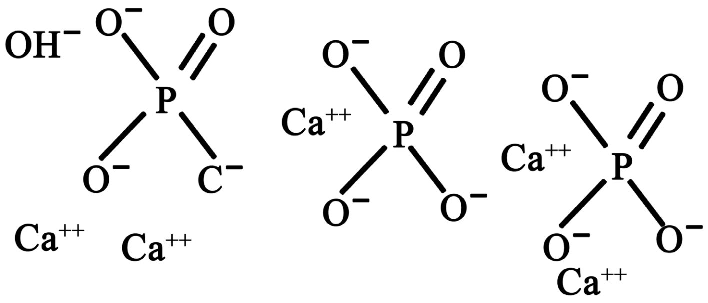


Figure 1. Molecular structure of hydroxyapatite [4].

4.2.2. Applications in Dental Implantology

Hydroxyapatite has been used for many years as a coating for titanium implants (**Figure 2** and **Figure 3**) and has achieved promising results [4].

According to some reports, HA is directly linked to bone, as there is no precise cause for this phenomenon more biological and clinical research is needed. Recently, nanotechnology has enabled the low-cost preparation of hydroxyapatite in micro and nano forms, increasing reactivity and surface area through "bottom-up" methods, as a result developping HA nano-cast dental implants that are capable of creating a chemical connection with the bone, promoting better bone integration and better biological fixation. However, controversies persist regarding HA-coated implants, with difficulties in correlating the properties of the coatings to their influence on bone formation and the long-term success and survival of the implants, due to limited data and variabilities between the studies reported on: [3] [4]

- The definition and duration of survival/success of the implant;
- The implant case and site selection;
- Surgeon experience, surgical protocols, post-operative regimens, recovery process;
- The characteristics of the coating and the prosthetic restoration.

Since 1981, efforts have been made to improve osseointegration and osteogenesis of dental implants by HA coatings, although these are more fragile compared to zirconium aluminum oxide ceramics, the hydroxyapatite has been studied for its use as a coating on metal implants, for its porous structure and resembles the inorganic structure of teeth and bone [9] [17].

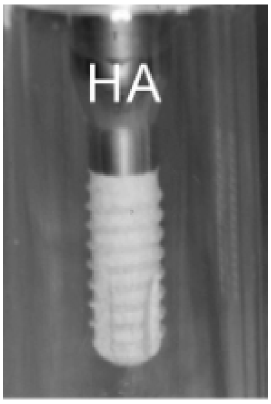


Figure 2. Titanium implant coated with hydroxyapatite [6].

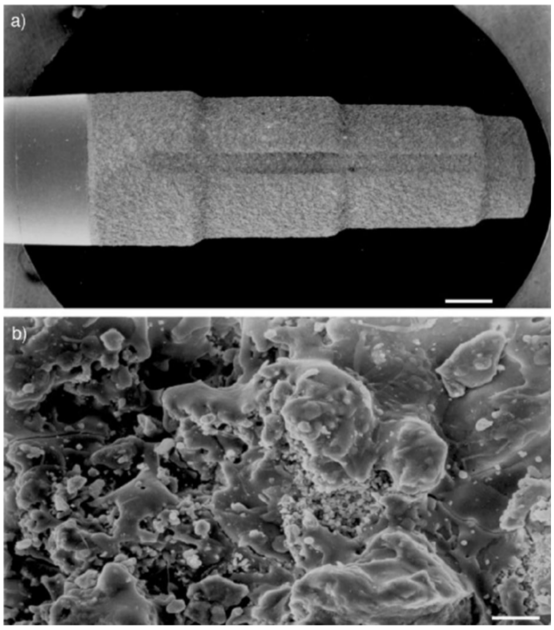


Figure 3. Dental implants (by Friadent) coated with CaP by a plasma spray process (a: 10×, b: 1000× magnification; a : 1mm; b: 10 μm scale bars) [7].

In alkaline and neutral aqueous solutions, HA dissociates quite quickly. It was thought that the negative effects on bone formation were minimal; here, the release of unwanted metal ions is caused by the disruption of HA on the passive oxide layer of the titanium implant surface. According to the literature, HA-coated implants show better bone integration, reaching 75.9% after three months, compared to 45.7% for titanium metal implants, although after six months, there is no significant difference between ceramic coated and uncoated metal implants. It should also be noted that the HA coating helps create an additional interface between the bone surface and the implant, which could be a potential cause of failure. Nanocrystalline HA powders, used for coating, have improved synthesis capacity, increased surface area and better densification, reducing the synthesis temperature. Clinical studies have revealed that HA-coated titanium implants have greater longevity than uncoated ones [7] [9] (**Figure 4**).

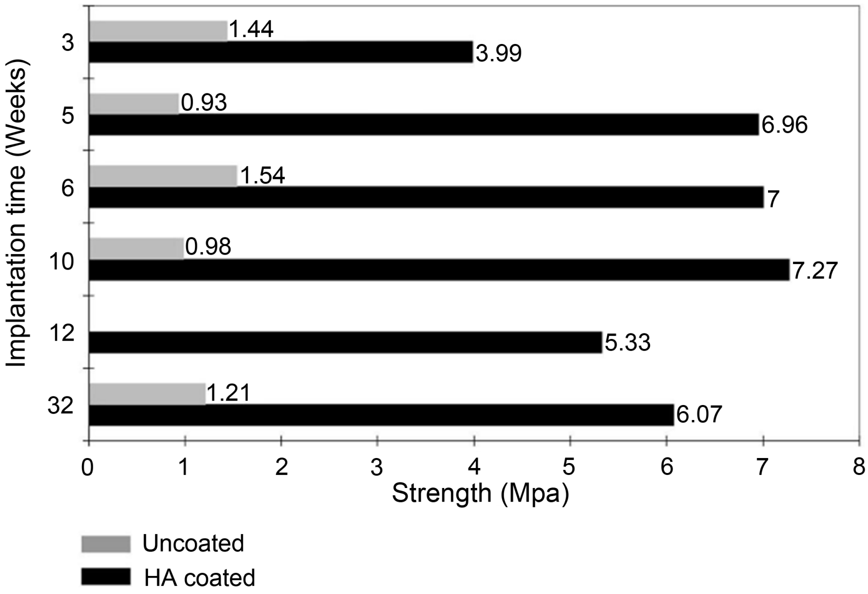


Figure 4. Plasma-sprayed HA coating shows improvement in strength compared to uncoated porous titanium [7].

4.2.3. Synthesis of Hydroxyapatite

There are many ways in which hydroxyapatite can be synthesized. Here are the most common methods [7] [9]:

- Wet methods including precipitation method, hydrothermal techniques and calciumphosphate hydrolysis.
- Solid state reactions.
- Ultrasonic irradiation.
- Sol-gel method.
- Microwave irrigation.
- Chemical precipitation.
- Microemulsion.

4.3. Hydroxyapatite Coating Processes

For hydroxyapatite to be used as a dental implant coating, the following conditions must be met: crystallinity of 62%, phase purity of 95%, density of 2.98 g/cm^3, a Ca/P ratio of 1.67 to 1.76, a cutting strength of more than 22 MPa and a tensile strength of more than 50.8 MPa [9].

The following figure shows the different methods used to coat implants with hydroxyapatite. (**Figure 5**)

- **Plasma spraying:**

Plasma spraying is a common method for applying hydroxyapatite coatings on implants. Studies have shown that the coating is prone to cracking and lack of adhesion. The temperatures required during the coating process can have negative effects on the prosthesis, such as a change in the crystal structure, the formation of a highly crystallized HA surface, and possible misorientation of the layer [9].

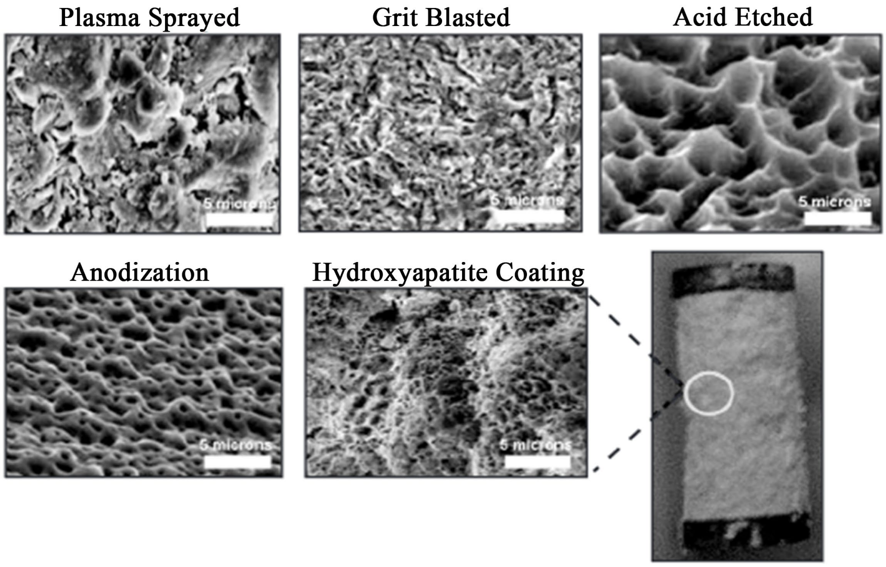


Figure 5. Some hydroxyapatite coating methods [9].

- **Electrophoretic deposition:**

This method requires the application of an electrical charge to both the surface of the hydroxyapatite and the titanium implant. The electrically charged hydroxyapatite particles are attracted to the implant surface and deposit there, creating a uniform coating. The ceramic layers are produced using the electrophoretic deposition (EPD) technique. It is an electrochemical process that takes place in a colloidal environment. In this procedure, a titanium implant is immersed in a solution containing calcium and phosphate ions, which react on the surface of the implant to form hydroxyapatite [9] (**Figure 6**).

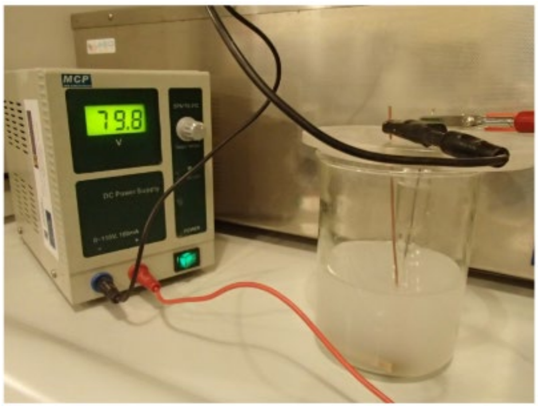


Figure 6. Electrophoretic equipment [1].

- **Sol-Gel Dip-coating technique:**

The process begins by dispersing the precursor particles in an aqueous or alcoholic solution, creating a colloidal suspension, also called sol. Subsequently, the addition of catalysts to the soil promotes polymerization reactions with hydrolysis and polycondensation, which form a gel (See **Table 2**). The dip coating method (DCM) involves well-controlled immersion. The DCM includes five different phases [9]

1) Immerse the pretreated titanium implant into the coating mixture at a specified rate.

2) Leave the implant immersed in the mixture for a while.

3) Remove the implant from the mixture, causing a film of liquid to form on the surface of the implant.

4) Drain the excess liquid to apply the new fixation to the implant surface.

5) Nanocrystalline hydroxyapatite can be synthesized using a variety of techniques, including hydrothermal, mechanochemical, precipitation, hydrolysis, and sol-gel.

- **Sputter deposition:**

This technique requires the use of a cathodic arc to vaporize the specific hydroxyapatite, which is then applied to the surface of the titanium implant. Electrochemical deposition is a process in which a solution containing the desired metal ion or its chemical complex can be electrolyzed to produce a thin, adherent layer of metal, oxide, or salt on the surface of a conductive substrate. By adjusting electrochemical deposition parameters such as pH, temperature and voltage as well as immersion time during the coating process, this technique can overcome the phase transition problems of HA coatings caused by PS and change the morphology of the HA coating [9].

- **Biomimetic coating:**

This is a relatively new method that produces heterogeneous nucleation and crystal growth of the coating with tissue-like properties. To do this, the implant surface is pretreated with alkaline (NaOH) or acidic (HF or HCl) solutions or heat treatment. The substrate is then immersed in simulated body fluid (SBF) at a body temperature of 37 degrees Celsius and a physiological pH of 7.4. SBF should have an ionic concentration similar to that of human blood plasma. CaP-based coatings are deposited on the implant surface after several weeks of SBF [17].

- **High Velocity Suspension Flame Spraying Technique (HVSFS):**

It is a new method for obtaining dense nanostructured surface coatings on the surface of a titanium implant. The powder is dispersed in an aqueous or organic solvent and introduced axially to the combustion chamber of a high-speed oxy-combustion modified spray cloth. This is because traditional high-velocity oxygen spray (HVOF) processes are not suitable for producing nanoparticle coatings. The powder is processed as a suspension (in an aqueous or organic solvent) to solve problems associated with handling nanoparticle powders, and its delivery is facilitated by relatively simple thermal spraying techniques [17].

- **Physical Vapor Deposition (PVD):**

These are vacuum deposition techniques in which materials are vaporized or pulverized. Two physical processes can be used to generate steam:

1) Thermal evaporation: The material is heated until its vapor pressure exceeds ambient pressure.

2) Cathodic sputtering and ejection of neutral atoms, for example by moving an ion beam and sputtering a magnetron. It is very useful for the deposition of HA [17].

- **Chemical Vapor Deposition (CVD):**

CVD and PVD are similar in the basic process of using steam and creating a thin film on a substrate. It does not produce vapor from a solid or liquid source in the vacuum chamber, which distinguishes it from PVD. Instead, vapors or gases are introduced into the chamber from an external source and, following a chemical reaction, are deposited on the substrate surface as non-solid volatiles in many directions. Unlike PVD, it is based on the chemical reaction of precursors in the gas phase [17].

- **Pulsed Laser Deposition (PLD):**

It is a physical vapor deposition (PVD) method in which a high-power pulsed laser is focused in a vacuum chamber to target the material to be deposited. In this situation, a laser with high power density and narrow frequency bandwidth is used as the evaporation source for the desired material, and there are almost no restrictions on the material used. This method can be considered when other methods have failed to achieve deposition and have been used to synthesize nanotubes and nanopowders [17].

Table 2. The following table shows the advantage/disadvantage ratio of the different techniques used [9].

Technical	Thickness	Benefits	Disadvantages
Thermal spraying	30 - 200 nm	• High deposit rate • Low cost	• High temperatures • Induces decomposition • Rapid cooling produces amorphous coatings
Pulsed laser deposition	0.05- 5 mm	• The coatings are crystalline amorphous dense and porous	• sight technique
Dynamic mixing methods	0.05 - 1.3 mm	• High adhesive strength	• sight technique • Expensive • Produces amorphous coatings
Dip coatings	0.05 - 0.5 mm	• Coatings are inexpensive and can be applied quickly • Can cover complex surfaces	• Requires high synthesis temperatures • Thermal expansion fault
Sol-gel	<1 mm	• Used to cover complex shapes • Low processing temperatures • Cheap process because the coatings are very thin	• Some processes require controlled amorphous processing • Expensive raw materials
Electrophoretic deposition	0.1 - 2.0 mm	• Uniform coating thickness • Fast deposit rate • Can be used to coat complex substrates	• Difficult to produce coatings without cracks • Requires high synthesis temperatures

Continued

Biomimetic coating	<30 mm	• Low processing temperatures • Results in the formation of bone apatite • Can take on complex shapes • May incorporate bone growth stimulating factors	• Time consumption • Requires constant filling and pH of stimulated body fluid
Hot isostatic pressure	0.2 - 2.0 mm	• Produces dense coatings	• Impossible to cover complex substrates • High temperature required • Thermal expansion fault • Difference in elastic property • Expandable • Interaction of the encapsulated material
Cathode sputtering	0.5 - 3 mm	• Uniform coating thickness on flat substrates • Dense coatings	• sight technique • Expensive • Time-consuming • This technique produces amorphous coatings

4.4. Overall Clinical Performance of Hydroxyapatite-Coated Dental Implants

4.4.1. Representative Table

We compiled 18 studies (Table 3) from various authors who conducted research with the aim of exploring the clinical performance of HA-coated Ti dental implants and improving the osseointegration and biocompatibility of these devices.

Table 3. Representative table of the results of the selected articles.

Name of authors	Purpose of the experiment	Method	Status	Results
López Valverde *et al.* [2]	To evaluate the osseointegration effectiveness of titanium (Ti) dental implants using bioactive surfaces compared to that of Ti implants using conventional surfaces	Following PRISMA guidelines, relying on the PICO framework for search strategy, selection of independent reviews and assessment using the Cochrane Collaboration tool.	Systematic review	Bioactive surfaces on dental implants improve osseointegration. Bone-to-implant contact surface area is higher for bioactive surfaces compared to control implants. Certain coating biomolecules have an early impact of the peri-implant on bone formation.
Mistry *et al.* [5]	Analysis and comparison of the clinical results (osseointegration) of dental implants in hydroxyapatite, bioactive glass and titanium alloy wire-machined in the human jaw bone after their implantation.	Evaluations of the result up to 12 months after prosthetic rehabilitation based on different clinical and radiological criteria. The use of the laser profilometer to evaluate the surface roughness of the implants studied.	In vivo	Safety and osseointegration efficiency is higher in bioactive glass coated implants than hydroxyapatite coated and machined titanium implants. They can be used as an alternative coating for dental implants.
Madi *et al.* [16]	To analyze the consequences of peri-implantitis caused by ligation on dental implants with and without hydroxyapatite (HA) coating.	Histological examination of implants containing surrounding tissues that were inserted into the jaws of canines, with 4 surface treatments. The study of implant surfaces and bone-to-implant contact (BIC) using scanning electron microscopy and energy-dispersive X-ray spectroscopy.	In vivo	Histological analysis: Decrease in bone around the implant and extensive infiltration of inflammatory cells into the surrounding soft tissue. The BIC (Bone-to-implant contact) of sputtered HA implants was highest (98.1%) than machined implants (70.4%). The disappearance after 28 weeks of the HA layer of cathode sputtering unlike plasma sputtering.
Mela *et al.* [8]	To analyze the performance of nano-hydroxyapatite coating and bone integration of early loaded dental implants in the posterior jaw.	In the Department of Oral and Maxillofacial Surgery of the Faculty of Dentistry of Mansoura University in Egypt, carrying out a clinical study on ten patients who need twelve implants (root-shaped) with early loading.	In vivo	Increase in the surface energy of titanium by the HAnano® coating combined with its microtopography.

Continued

Clavell *et al.* [14]	Optimize HA coating times to stabilize bone surfaces of Ti-6Al-4V samples and evaluate cell adhesion and growth to determine the effect of HA topographies and identify the best acellular coating time for development optimal biological.	The method employed consists of proposing an in vitro ceramic coating, evaluating optimal coating times, performing SEM and EDS analyses, as well as experimenting with human dental pulp stem cells.	In vitro	Treatment of titanium alloys with HA coatings by simulated immersion of body fluid and the formation of porous clusters of HA cauliflores on a flat coating, after 8 to 12 days. Change in the composition of the ceramic layer initially into salts then apatites, with a Ca/P ratio comparable to that of physiological hydroxyapatite. Short incubation periods promote cell adhesion, while long culture periods result in hydroxyapatite deposition.
Bral and Mommaerts. [13]	To describe the best procedures for increasing osseointegration in cranio-maxillofacial surgery using nano calcium phosphate coatings on patient-specific titanium implants.	A systematic review of the literature using a multiple database and a single reviewer was performed. Twenty-eight works composed of twenty-five studies on animals and three on humans	Systematic review	Titanium implants coated with calcium nanophosphate and hydroxyapatite improve osseointegration and implant fixation. While not all coating techniques improve biofunctionalization. Implant microroughness, coating thickness, calcium phosphate solubility, and nanotopography contribute significantly to biofunctionalization. However, additional clinical studies are needed to confirm this.
Święczko *et al.* [1]	To analyze how the electrophoretic method is used to create hydroxyapatite coatings on titanium alloys and evaluate the benefits of electrophoretic deposition (EPD) in creating ceramic layers.	Samples of Ti-6Al-4V and Ti1-3Zr1-3Nb alloys were cut, polished and coated with hydroxyapatite to conduct electrophoretic studies. After applying a solution of hydroxyapatite in ethyl alcohol, they were heated at 500˚C for 20 minutes and subjected to 60V of electricity for 7 minutes. The samples were analyzed using an electron microscope and then immersed in bacterial liquid for 1 - 3 months to observe bacterial adhesion with a biological microscope.	In vitro	Ti13Zr13Nb alloy was not associated with bacteria and biofilms after 6 months, while Ti-6Al-4V bond showed separated bacteria after 3 months and full biofilm coverage after 6 months. The EPD method quickly forms layers that can be controlled in thickness and morphology, and the hydroxyapatite coatings increase abrasion resistance and protect against unwanted compounds.
Kato *et al.* [6]	To retrospectively analyze the 10-year clinical results of HA-coated implants (HA implants) by comparing them with the same system implants with a titanium oxidized anodic surface (Ti implants).	Life table analysis was used to calculate the cumulative survival rate (CSR) of HA or Ti implants implanted in 183 patients (55 aged 12.4 years) over a twenty-year period. RCS differences were compared in each year based on interval, gender, age and frequency of number of placements based on location and implant diameter for both implant types.	In vivo	HA implants showed better long-term stability at the upper molar site compared to Ti implants, with cumulative success rates of 89.9% and 77.7% respectively after 10 years. HA implants showed a preferential distribution at the upper molar site and tended to have a larger diameter than Ti implants, with no notable variation in RCS over the course of a year.
Salaie *et al.* [12]	improving the biocompatibility of Ag NP-coated titanium dental implants with surface-applied hydroxyapatite (HA)	The experimentation involved coating a medical titanium alloy with an Ag NP surface for an antibacterial coating, then adding a layer of hydroxyapatite for biocompatibility. The coatings were prepared and characterized, then osteoblast cells were cultured on these discs for seven days to assess their health and function.	In vitro	Silver and HA nanoparticles were successfully applied to implants, providing long-lasting coatings and slow release of silver over 7 days. Osteoblasts retained normal morphology and 70% viability with Ag-nHA, demonstrating superior biocompatibility to Ag-mHA or Ag alone.
Sartoretto *et al.* [10]	To analyze implant surface structure and biomechanical, histomorphometric and histological bone reactions to a novel nanostructured hydroxyapatite surface implanted in the iliac crest of sheep.	This study compares three types of dental implants in female sheep aged 2 to 4 years. Thirty implants (n = 10/group): HAnano® coated (Epikut Plus®, SIN Implant System, Sao Paulo, SP, Brazil), SLActive (BLX®, Straumann, Basel, Switzerland) and TiUnite (NobelActive®, Nobel Biocare, Gothenburg, Sweden) were analyzed for their topography, insertion torque value, and resonance frequency via electron microscopy. Primary stability, bone-to-implant contact and bone fraction were assessed after 14 and 28 days.	In vivo	The implant surfaces were similar, except for TiUnite®, which stood out. The average insertion torques were 74 (±8.9) N/cm for SLActive® and TiUnite®, and 72 (±8.3) N/cm for HAnano® ($p > 0.05$). All groups showed a significant increase in bone-to-implant contact and bone fraction rates after four weeks, reaching over 80% and approximately 60% respectively, with no significant differences between groups.

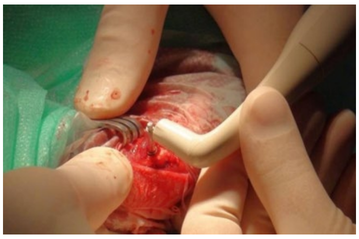
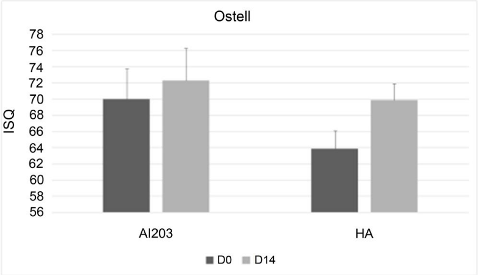
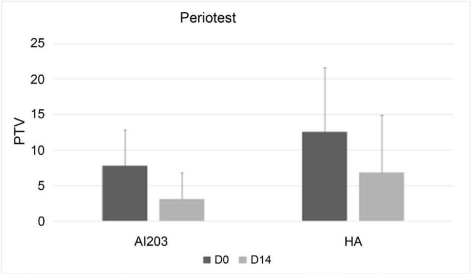
Continued

Łukaszewska-Kuska *et al.* [18]	endosseous titanium implants in rabbits using a modified electrochemical method.	Rabbit tibias were fitted with titanium implants with HA coatings and controls with gritt-blasted Al_2O_3 surfaces. The chemical composition, roughness and morphology of the implants were established. Implant stability tests were carried out and Periotest ® (PTV) and Implant Stabilization Coefficient (ISQ) values were recorded for Osstell Mentor to assess their bone integration.	In vivo	Implant surface characteristics impact implant stability, as shown by Osstell and Periotest measurements. The HA coating mentioned in this paper exhibited chemical and physical characteristics that appeared to favor osseointegration compared to grit -blast implants.
Lee *et al.* [19]	The aim is to demonstrate that different human periodontal cells can be combined on a titanium implant.	The bio-implants, which are made of hydroxyapatite-coated titanium screws, are used to coil cell sheets from immortalized human periodontal cells, which have been transplanted into a mouse model used for dental extractions. A stereomicroscope was used to analyze the tissues by excising, fixing, decalcifying and staining them.	In vivo	Over the course of 8 weeks, the bio-implant promoted the formation of fibrous connective tissue, blood vessels and bone growth integrated into the alveolar bone base. The use of human cells allowed a partial reconstruction of the natural dental attachment complex, including cement, PDL and alveolar bone. Research has demonstrated that periodontal tissues can be restored with cell sheets around the dental implant, without the use of embryos.
Liu *et al.* [20]	Development of a dual-functional titanium alloy with nano-hydroxyapatite coating for sustained release of HBD-3 and BMP-2, providing protection against bacterial infections in orthopedic and dental clinic, while improving osteogenesis of implants in titanium in dental and bone treatments.	The method involved manufacturing HA-Ti using a dip coating technique, loading it with HBD-3 and BMP-2, and evaluating the encapsulation efficiency using specific genetic markers.	In vivo	The bio-functional titanium alloy with nano-hydroxyapatite coating enabled sustained release of antimicrobial peptides b- defensin 3 (HBD-3) and bone morphogenetic protein2 (BMP-2). This material inhibited the growth of Gram-negative and Gram-positive bacteria after 7 days of incubation, with an absence of viable bacteria. Furthermore, it promoted the adhesion, proliferation and osteogenic differentiation of human bone marrow mesenchymal stem cells (hBMSCs) under the same conditions.
Szabo *et al.* [21]	Develop Al2O3-HA coatings by HVOF sputtering to improve the wear resistance and biocompatibility of titanium substrates. The incorporation of alumina into these coatings significantly increases the durability of titanium	The methodology involved the use of a high-velocity oxygen fuel (HVOF) thermal spray process for coating deposition, scanning electron microscopy (SEM) and X-ray diffraction techniques for identification of microstructure and phase, measuring surface roughness and determining sliding wear using a pin on the disk tribometer.	In vitro	Al_2O_3-HA coatings significantly improve the wear resistance of the titanium substrate, with the presence of alumina improving the wear resistance by approximately 2 - 3 times. The structure of hydroxyapatite has not undergone significant changes, which is important for the restoration of bone tissue.
He *et al.* [22]	Improving the performance of common titanium and its alloys, with regard to their bioactivity and their speed of osseointegration, in the field of orthopedic implants.	A functional triple-layer coating, consisting of a porous outer layer of hydroxyapatite (HA), an intermediate fluoro -HA layer (FHA) and an inner layer of titanium oxide (TiO_2), was developed on a titanium substrate using a multi-step sol-gel method. Using X-ray diffraction, the presence of anatase TiO_2 and apatite crystallization was noted in the coating.	In vitro	Electron microscopy revealed strong bonding of the ~2 mm thick coating, with good adhesion resistance. Tests showed excellent biological compatibility and osteoblasts with better proliferation and ALP activity than pure titanium or HA coatings.
Yazdani *et al.* [4]	To examine the impact of nano-hydroxyapatite on osseointegration of titanium implants by conducting a literature review, analyzing implant and nanotechnology data, evaluating the ability of HA nanoparticles to bind to tissues dental, determining the long-term stability of the HA/bone interface and identifying needs for future research on the cell-substrate interface to optimize implants.	The methodology used in the study involved a literature review using electronic databases and MeSH keywords to collect relevant literature published in English on the effect of nano-hydroxyapatite on osseointegration of implants. titanium, without any limitation on the publication date. Data regarding titanium implants, nanotechnology, nano-hydroxyapatite, osseointegration and cell attachment were collected and reviewed.	Literature review	Hydroxyapatite coatings for dental materials have shown improved bone tissue integration to the coating implant surfaces. The release of calcium and phosphate ions from HA coatings as a result of degradation and dissolution may play a role in accelerating bone adaptation to these surfaces. The degree of crystallinity of HA plays a key role in the initial cellular interaction with implant surfaces.

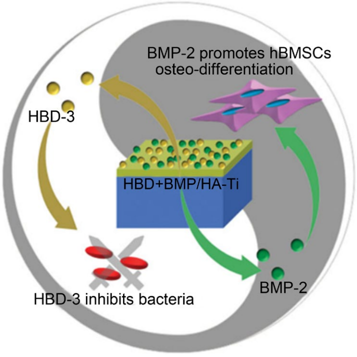
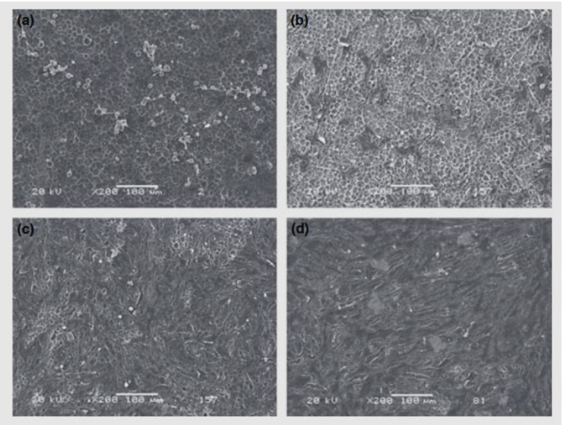
Continued

Kylychbekov *et al.* [31]	The use of pulsed laser sputtering makes it possible to study the effects of substrate temperature on the properties of hydroxyapatite (HA) coatings applied to Ti_6Al_4V and Si(100) surfaces. The analyzes focus on the structural, mechanical and bioactive properties of the coatings, taking into account the deposition temperature and the ablation process.	The Si(100) and Ti6Al4V surfaces received HA coatings. The substrate temperature varied from room temperature to 800˚C. The depositions were carried out in Ar/H_2O environments and under vacuum. Structural and morphological variations were analyzed by X-ray diffraction, scanning electron microscopy and atomic force microscopy. The shrinkage method was used to evaluate the adhesion of the coatings to the substrates.	In vitro	The coatings crystallize uniformly at increasing temperatures, but above 700˚C, protein adsorption and adhesion properties degrade. Tests show that crystallinity, influenced by deposition conditions, is crucial to coating performance. However, the morphostructural, mechanical and bioactive properties deteriorate above 700˚C.
Ma *et al.* [32]	To study the effect of a hydroxyapatite layer deposited on titanium implants with a pulsed erbium-doped yttrium and aluminum laser on the polarization of M2 type macrophages in vitro and on osteogenesis in vivo	In vitro and in vivo experiments to evaluate the effect of a laser-applied hydroxyapatite layer on titanium implants. Titanium plates and screws were coated with hydroxyapatite and polarization by M2 macrophages, osteogenic properties and osseointegrative activity were evaluated.	In vitro/In vivo	Erbium-doped hydroxyapatite-coated titanium implants improve hard tissue differentiation, M2 macrophage polarization, and bone formation, providing improved osseointegration and long- term clinical success
Hou *et al.* [33]	multidoped HA coatings on titanium discs and implants to improve both osteogenesis and antibacterial properties against Porphyromonas gingivalis and Prevotella nigrescens	Human embryonic palatal mesenchymal cells were analyzed for mRNA and protein levels of osteogenesis-related genes (COL1A1, DCN, TNFRSF11B, SPP1). Antibacterial properties against Porphyromonas gingivalis and Prevotella nigrescens have been studied. Histological examination and CT scan assessed bone formation in rats	In vivo	ZnSrM-HA group showed the best results in stimulating the expression of key mRNAs and proteins and exhibited significant bone growth. Additionally, ZnSrMg-HA and Zn-HA groups were found to be effective against P. gingivalis and P. nigrescens. A porous coating of ZnSrMg-HA with VIPF-APS could be innovative for coating titanium implants and preventing bacterial infections.

4.4.2. Table of Figures (see Figures 7-12)

Name of authors	Figures	
Łukaszewska-Kuska *et al.* [18]	 **Figure 7.** Implant stability test with an Ostell device. Measurements were made in 2 directions, with the instrument parallel and perpendicular to the longitudinal axis of the tibia. Mean ISQ values were recorded [18].	 **Figure 8.** Testing implant stability with a periotest. The measurements were made at the same point from the rolled abutment to the implants. During measurements, the Periotest handle was always kept perpendicular to the abutment axes [18].
	 **Figure 9.** Values of the stability coefficient of HA-coated and sandblasted implants at the time of implantation and after 2 weeks of healing. Each value is a mean ± standard deviation (SD). Statistically significant differences were observed for measurements between the time of implantation and the time of sacrifice for HA-coated implants (p = 0.006), while for Al_2O_3 coated implants there were had an increase in ISQ values, not significant (p = 0.15). [18]	 **Figure 10.** Periotest values of HA-coated and sandblasted implants at the time of implantation and after 2 weeks of healing. Each value is a mean ± standard deviation (SD). Statistically significant differences were observed between measurements between the time of implantation and the time of animal sacrifice for the Al_2O_3 sandblasted implants (p = 0.01) and for the implants coated with a HA coating (p = 0.04). [18]

Continued

by Liu *et al.* [20]	 **Figure 11.** A biofunctional titanium alloy with a nano-hydroxyapatite coating (HBD þ BMP/HA-Ti), which enables sustained simultaneous release of the natural antimicrobial peptide human b-defensin 3 (HBD-3) and bone morphogenetic protein-2 (BMP-2). It shows combined antibacterial and osteogenic effects for potential application in clinical dental and bone therapy. [20]
He *et al.* [22]	 **Figure 12.** Electron microscopy scanning the morphology of osteoblasts cultured on the TiO_2/FHA/HA coating after (a) 1 day; (b) 3 days; (c) 5 days and (d) 7 days. [22]

4.4.3. Clinical Performance Aspects of Hydroxyapatite-Coated Ti Dental Implants

From the results of this compilation we have raised several aspects of the clinical performance of Ti dental implants coated with hydroxyapatite:

- **Improved osseointegration**: Results show significantly improved bone-to-implant contact compared to untreated or conventional surfaces, as hydroxyapatite-coated surfaces appear to promote better bone integration. This indicates better stability and anchoring of the implants in the surrounding bone [2] [4] [5] [8] [13] [18] [31]-[33].

- **Reduction of infections:** Some coatings, such as those that combine silver nanoparticles with hydroxyapatite, show a slow, prolonged release of silver, which can help prevent bacterial infections around dental implants [1] [31] [33].

- **Increased Biocompatibility:** It appears that hydroxyapatite coatings promote better adhesion, proliferation and differentiation of bone cells, which contributes to a favorable cellular response and better integration of implants with surrounding bone tissues [12] [20] [31] [32].

- **Long-term durability and stability:** According to long-term studies, hydroxyapatite-coated implants may provide superior long-term survival and stability compared to uncoated implants. These results are essential to guarantee the long-term success of implant -prosthetic treatments [7] [16] [21] [31].

- Reduced risk of inflammatory reactions: Hydroxyapatite coatings can help prevent inflammatory reactions around implants by promoting better integration with bone tissue and reducing unwanted immune response [12] [20] [33].

- Potential for tissue regeneration: Certain coatings, such as those that combine human periodontal cells with hydroxyapatite, have the potential for periodontal tissue regeneration, offering therapeutic prospects for reconstruction of the tooth attachment complex and tissue regeneration periodontal [19] [20] [31] [33].

4.5. Comparision with Conventional Dental Implants Not Coated with Hydroxyapatite

Hydroxyapetite-coated implants present several advantages over conventional implants, particularly in osseointegration and long-term performance. The following overview outlines key differences and similarities between the two:

- **Effectiveness of osseointegration:** Dental implants with bioactive surfaces show potential for improvement over conventional surfaces, according to limited studies [2] [5].

- **Bone-implant contact surface**: HA-coated implants provide a more favorable bone-implant contact surface than conventional implants, with a statistically significant distinction [2].

- **Favorable effect on osseointegration:** Some bioactive coatings have demonstrated a positive effect on osseointegration by influencing bone formation around the dental implant [2].

- **Long-term survival:** HA-coated implants showed a higher cumulative survival rate up to 8 years after placement, particularly at the upper molar site, although no significant differences were observed after 10 years [6] [23].

Clinical studies have also shown that the lifespan of an implant coated with an HA layer is much longer than that of the implant without a layer [7].

- **Effective alternative**: Bioactive glass implants may be as effective as HA-coated titanium implants in achieving osseointegration, providing an alternative to conventional implants [5] [24].

- **Risk of peri-implantitis:** Implants fully coated with HA do not appear to significantly increase the risk of peri-implantitis compared to implants partially coated with HA [24].

- **Biocompatibility**: Implants coated with nano-hydroxyapatite present biocompatibility similar to conventional implants, according to studies carried out [11] [15].

Hydroxyapatite-coated implants show potential benefits in osseointegration and long-term survival compared to conventional implants, although additional studies are needed to confirm these findings and fully evaluate their clinical effectiveness.

4.6. Future Prospects

Thanks to their ability to promote rapid and effective osseointegration, Ti-HA dental implants represent a major advance in the field of restorative odontology and implantology. Here are some perspectives for future implants:

- **Improved surface properties**: Research focuses on optimizing the surface microstructure of HA-coated implants to improve cell adhesion and accelerate osseointegration. More biologically reactive surfaces can be obtained using sophisticated methods such as plasma or laser processing [26].

- **Nano-coatings**: Using HA nano-coatings on titanium implants can improve bone integration and release substances that promote bone healing and growth in a controlled manner. Nanocoatings can also improve the durability and corrosion resistance of implants [27].

- **Biofunctionalization**: Adding peptides or proteins that specifically promote bone cell adhesion and proliferation to implant surfaces can increase the efficiency of osseointegration. This could allow treatment to be tailored to the unique needs of each patient [29].

Models for computer-assisted surgical prediction and planning: The increased use of computer-assisted surgical planning (CAOS) to optimize implant positioning and the creation of predictive models to evaluate the success of osseointegration based individual patient characteristics could improve clinical outcomes [18].

- **3D printing technology**: 3D printing allows the creation of personalized implants that perfectly adapt to each patient's bone geometry, which can improve bone integration and reduce healing time [25].

- **Long-term tracking and monitoring technologies**: Creating technologies that can monitor the integrity and function of implants in real time could enable rapid intervention if problems arise, thereby increasing the long-term durability of implants [28].

These ideas are based on a deep understanding of the biological interactions between the implant-bone interface as well as technological advances in materials and engineering. They could significantly improve outcomes for patients who need dental implants in terms of functionality, comfort and aesthetics.

5. Conclusions

In this work, we review advances in the field of dental implantology, particularly the use of hydroxyapatite (HA)-coated titanium implants and their impact on improving clinical performance. According to research, these implants offer better osseointegration and biocompatibility, allowing a stronger bond between the implant and the bone. This improvement is essential for patients requiring dental reconstructions, as it provides a better quality of life through reliable and durable solutions. During our study, HA-coated implants were shown to promote faster recovery and reduce the risk of postoperative complications compared to conventional titanium implants. This difference represents a significant evolution in the practice of dental implants and provides patients and professionals with a safer and more effective option. Despite the obvious benefits, obstacles still need to be overcome, particularly regarding the cost and accessibility of these modern technologies.

Additional research is therefore necessary to optimize these implants, reduce their cost and make them more accessible to a wider population. Furthermore, it is important to deepen the understanding of the biological mechanisms underlying the improved osseointegration of HA-Ti implants in order to develop innovative strategies to further improve their performance.

This work highlights the importance of interdisciplinary collaboration in dental implant research by combining the efforts of biomaterials, biology, engineering and clinical dentistry to advance our understanding and skills in this area.

This research is expected to contribute to significant advances in the design and use of dental implants, improving the health and well-being of patients around the world. Remember that continued research and innovation are necessary to address remaining challenges and make these advanced solutions more accessible.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Świeczko-Żurek, B. and Bartmański, M. (2016) Investigations of Titanium Implants Covered with Hydroxyapatite Layer. *Advanced Material Science*, **16**, 78-86. https://doi.org/10.3390/ijms24054933

[2] López-Valverde, N., Flores-Fraile, J., Ramírez, J.M., Macedo De Sousa, B., Herrero-Hernández, S. and López-Valverde, A. (2020) Bioactive Surfaces vs. Conventional Surfaces in Titanium Dental Implants: A Comparative Systematic Review. *Journal of Clinical Medicine*, **9**, 2047. https://doi.org/10.3390/jcm9072047

[3] Ong, J.L. and Chan, D.C.N. (2017) A Review of Hydroxapatite and Its Use as a Coating in Dental Implants. *Critical Reviews in Biomedical Engineering*, **45**, 411-451. https://doi.org/10.1615/CritRevBiomedEng.v45.i1-6.160

[4] Yazdani, J., Ahmadian, E., Sharifi, S., Shahi, S. and Maleki Dizaj, S. (2018) A Short View on Nanohydroxyapatite as Coating of Dental Implants. *Biomedicine & Pharmacotherapy*, **105**, 553-557. https://doi.org/10.1016/j.biopha.2018.06.013

[5] Mistry, S., Roy, R., Kundu, B., Datta, S., Kumar, M., Chanda, A., *et al.* (2016) Clinical Outcome of Hydroxyapatite Coated, Bioactive Glass Coated, and Machined Ti6Al4V Threaded Dental Implant in Human Jaws: A Short-Term Comparative Study. *Tooth Implant*, **25**, 252-260. https://doi.org/10.1097/ID.0000000000000376

[6] Kato, E., Yamada, M. and Sakurai, K. (2015) Retrospective Clinical Outcome of Nanopolymorphic Crystalline Hydroxyapatite-Coated and Anodic Oxidized Titanium Implants for 10 Years. *Journal of Prosthodontic Research*, **59**, 62-70. https://doi.org/10.1016/j.jpor.2014.11.004

[7] Pajor, K., Pajchel, L. and Kolmas, J. (2019) Hydroxyapatite and Fluorapatite in Conservative Dentistry and Oral Implantology—A Review. *Materials*, **12**, Article 2683. https://doi.org/10.3390/ma12172683

[8] Mela, O.A., Tawfik, M.A.M., Ahmed, W.M.A.S. and Abdel-Rahman, F.H. (2022) Efficacy of Nano-Hydroxyapatite Coating on Osseointegration of Early Loaded Dental Implants. *International Journal of Health Sciences*, **2022**, 696-712. https://doi.org/10.53730/ijhs.v6nS2.4998

[9] Ahmed, F., Rashid, H., Farookhi, S., Verma, V., Mulyar, Y., Khalifa, M., *et al*. (2015) Surface Modifications of Endosseous Dental Implants by Incorporation of Roughness and Hydroxyapatite Coatings. *Journal of the Pakistan Dental Association*, **24**, 162-171.

[10] Sartoretto, S.C., Calasans-Maia, J., Resende, R., Câmara, E., Ghiraldini, B., Barbosa Bezerra, F.J., *et al*. (2020) The Influence of Nanostructured Hydroxyapatite Surface in the Early Stages of Osseointegration: A Multiparameter Animal Study in Low-Density Bone. *International Journal of Nanomedicine*, **15**, 8803-8817. https://doi.org/10.2147/ijn.s280957

[11] de Wilde, E.A.W.J., Jimbo, R., Wennerberg, A., Naito, Y., Coucke, P., Bryington, M.S., *et al*. (2013) The Soft Tissue Immunologic Response to Hydroxyapatite-Coated Transmucosal Implant Surfaces: A Study in Humans. *Clinical Implant Dentistry and Related Research*, **17**, e65-e74. https://doi.org/10.1111/cid.12128

[12] Salaie, R.N., Besinis, A., Le, H., Tredwin, C. and Handy, R.D. (2020) The Biocompatibility of Silver and Nanohydroxyapatite Coatings on Titanium Dental Implants with Human Primary Osteoblast Cells. *Materials Science and Engineering*: *C*, **107**, Article 110210. https://doi.org/10.1016/j.msec.2019.110210

[13] Bral, A. and Mommaerts, M.Y. (2016) *In Vivo* Biofunctionalization of Titanium Patient-Specific Implants with Nano Hydroxyapatite and Other Nano Calcium Phosphate Coatings: A Systematic Review. *Journal of Cranio-Maxillofacial Surgery*, **44**, 400-412. https://doi.org/10.1016/j.jcms.2015.12.004

[14] Clavell, R.S., de Llano, J.J.M., Carda, C., Ribelles, J.L.G. and Vallés-Lluch, A. (2016) *In Vitro* Assessment of the Biological Response of Ti6Al4V Implants Coated with Hydroxyapatite Microdomains. *Journal of Biomedical Materials Research Part A*, **104**, 2723-2729. https://doi.org/10.1002/jbm.a.35817

[15] Xuereb, M., Camilleri, J. and Attard, N. (2015) Systematic Review of Current Dental Implant Coating Materials and Novel Coating Techniques. *The International Journal of Prosthodontics*, **28**, 51-59. https://doi.org/10.11607/ijp.4124

[16] Madi, M., Zakaria, O., Ichinose, S. and Kasugai, S. (2016) Effect of Induced Periimplantitis on Dental Implants with and without Ultrathin Hydroxyapatite Coating. *Implant Dentistry*, **25**, 39-46. https://doi.org/10.1097/id.0000000000000331

[17] Sharma, A. (2023) Hydroxyapatite Coating Techniques for Titanium Dental Implants—An Overview. https://www.qeios.com/read/2E6UHN

[18] Łukaszewska-Kuska, M., Krawczyk, P., Martyla, A., Hedzelek, W. and Dorocka-Bobkowska, B. (2019) Effects of a Hydroxyapatite Coating on the Stability of Endosseous Implants in Rabbit Tibiae. *Dental and Medical Problems*, **56**, 123-129. https://doi.org/10.17219/dmp/103851

[19] Lee, D., Lee, J., Kim, E., Takata, T., Abiko, Y., Okano, T., *et al*. (2017) Bio-Implant as a Novel Restoration for Tooth Loss. *Scientific Reports*, **7**, Article No. 7414. https://doi.org/10.1038/s41598-017-07819-z

[20] Liu, H., Wei, D., Deng, J., Zhu, J., Xu, K., Hu, W., *et al*. (2018) Combined Antibacterial and Osteogenic *in Situ* Effects of a Bifunctional Titanium Alloy with Nanoscale Hydroxyapatite Coating. *Artificial Cells*, *Nanomedicine*, *and Biotechnology*, **46**, 460-470. https://doi.org/10.1080/21691401.2018.1499662

[21] Szabo, A., Utu, I.D., Hulka, I., Bordeasu, I. and Mitelea, I. (2018) Microstructure and Wear Behaviour of Ti Reinforced HVOF Coating. *IOP Conference Series: Materials Science and Engineering*, **416**, Article 012007. https://doi.org/10.1088/1757-899x/416/1/012007

[22] He, G., Guo, B., Wang, H., Liang, C., Ye, L., Lin, Y., *et al.* (2014) Surface Characterization and Osteoblast Response to a Functionally Graded Hydroxyapatite/Fluoro-Hydroxyapatite/Titanium Oxide Coating on Titanium Surface by Sol-Gel Method. *Cell Proliferation*, **47**, 258-266. https://doi.org/10.1111/cpr.12105

[23] Arghami, A., Simmons, D., St. Germain, J. and Maney, P. (2021) Immediate and Early Loading of Hydrothermally Treated, Hydroxyapatite-Coated Dental Implants: A 7-Year Prospective Randomized Clinical Study. *International Journal of Implant Dentistry*, **7**, Article No. 21. https://doi.org/10.1186/s40729-021-00299-x

[24] Kim, H., Yun, P. and Kim, Y. (2016) Randomized Controlled Clinical Trial of 2 Types of Hydroxyapatite-Coated Implants on Moderate Periodontitis Patients. *Journal of Periodontal & Implant Science*, **46**, 337-349. https://doi.org/10.5051/jpis.2016.46.5.337

[25] Wijesinghe, W.P.S.L., Mantilaka, M.M.M.G.P.G., Chathuranga Senarathna, K.G., Herath, H.M.T.U., Premachandra, T.N., Ranasinghe, C.S.K., *et al.* (2016) Preparation of Bone-Implants by Coating Hydroxyapatite Nanoparticles on Self-Formed Titanium Dioxide Thin-Layers on Titanium Metal Surfaces. *Materials Science and Engineering: C*, **63**, 172-184. https://doi.org/10.1016/j.msec.2016.02.053

[26] Lugovskoy, A. and Lugovskoy, S. (2014) Production of Hydroxyapatite Layers on the Plasma Electrolytically Oxidized Surface of Titanium Alloys. *Materials Science and Engineering: C*, **43**, 527-532. https://doi.org/10.1016/j.msec.2014.07.030

[27] Carradò, A., Perrin-Schmitt, F., Le, Q.V., Giraudel, M., Fischer, C., Koenig, G., *et al.* (2017) Nanoporous Hydroxyapatite/Sodium Titanate Bilayer on Titanium Implants for Improved Osteointegration. *Dental Materials*, **33**, 321-332. https://doi.org/10.1016/j.dental.2016.12.013

[28] Fathi, A.M., Ahmed, M.K., Afifi, M., Menazea, A.A. and Uskoković, V. (2020) Taking Hydroxyapatite-Coated Titanium Implants Two Steps Forward: Surface Modification Using Graphene Mesolayers and a Hydroxyapatite-Reinforced Polymeric Scaffold. *ACS Biomaterials Science & Engineering*, **7**, 360-372. https://doi.org/10.1021/acsbiomaterials.0c01105

[29] Tao, Z., Zhou, W., He, X., Liu, W., Bai, B., Zhou, Q., *et al.* (2016) A Comparative Study of Zinc, Magnesium, Strontium-Incorporated Hydroxyapatite-Coated Titanium Implants for Osseointegration of Osteopenic Rats. *Materials Science and Engineering: C*, **62**, 226-232. https://doi.org/10.1016/j.msec.2016.01.034

[30] Silva, R.C.S., Agrelli, A., Andrade, A.N., Mendes-Marques, C.L., Arruda, I.R.S., Santos, L.R.L., *et al.* (2022) Titanium Dental Implants: An Overview of Applied Nanobiotechnology to Improve Biocompatibility and Prevent Infections. *Materials*, **15**, Article 3150. https://doi.org/10.3390/ma15093150

[31] Kylychbekov, S., Allamyradov, Y., Khuzhakulov, Z., Majidov, I., Banga, S., ben Yosef, J., *et al.* (2023) Bioactivity and Mechanical Properties of Hydroxyapatite on Ti6Al4V and Si(100) Surfaces by Pulsed Laser Deposition. *Coatings*, **13**, Article 1681. https://doi.org/10.3390/coatings13101681

[32] Ma, L., Li, M., Komasa, S., Hontsu, S., Hashimoto, Y., Okazaki, J., *et al.* (2023) Effect of Er: YAG Pulsed Laser-Deposited Hydroxyapatite Film on Titanium Implants on M2 Macrophage Polarization *in Vitro* and Osteogenesis *in Vivo*. *International Journal of Molecular Sciences*, **25**, Article 349. https://doi.org/10.3390/ijms25010349

[33] Hou, H., Lee, B., Liu, Y., Wang, Y., Kuo, W., Chen, I., *et al*. (2023) Vapor-Induced Pore-Forming Atmospheric-Plasma-Sprayed Zinc, Strontium, and Magnesium-Doped Hydroxyapatite Coatings on Titanium Implants Enhance New Bone Formation—An *in Vivo* and *in Vitro* Investigation. *International Journal of Molecular Sciences*, **24**, Article 4933. https://doi.org/10.3390/ijms24054933