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REVIEW ARTICLE

Titanium Reinvented: A Comprehensive Review of Its Prosthodontic Advancements

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ABSTRACT
Titanium has revolutionized the field of prosthodontics due to its unique properties such as biocompatibility, high strength, and corrosion resistance. Over the years, advancements in material science and manufacturing techniques have further enhanced its utility in various prosthodontic applications. This review aims to provide a comprehensive overview of the recent advances and applications of titanium in prosthodontics, highlighting its role in improving treatment outcomes and patient satisfaction.
Keywords: Titanium, Prosthodontics, Biocompatibility, Patient, Treatment.

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INTRODUCTION

Since the 1980s, titanium and its alloys have been pivotal in dentistry due to their exceptional properties and biomedical versatility. Renowned for its biocompatibility, low elasticity, lightweight, and corrosion resistance, titanium emerged as a key material.[1]
Introduced inadvertently in the 1960s, Per-Ingvar Branemark's pioneering work solidified titanium's role, particularly in dental implants, with a remarkable 97% success rate reported in 1982. [2] Commercially pure titanium is preferred over alloys for dental implants due to concerns about alloying element release.[3]
Beyond dentistry, titanium finds extensive use in orthopedics and other medical fields. In dentistry, titanium is essential for various prosthetic solutions, providing reliable, long-lasting restorations.[4]
Advanced techniques like CAD/CAM and 3D printing have replaced traditional manufacturing methods, enabling precise customization. Recent advancements include nanostructuring and coatings with bioactive and antibacterial materials, enhancing implant surface properties for improved osseointegration.[5]
This article offers a concise overview of titanium's significance in dentistry, highlighting recent advancements and future prospects in prosthodontics and dental restoration.

MATERIAL AND METHODS

An electronic search was performed on EMBASE, EBSCO, Web of Science, Medline/PubMed, and Cochrane Library databases for the articles published from 1988 to 2022. Finally, 41 articles were collected, and they were used to formulate this review. . The selected literature was critically analyzed to extract key findings related to advancements and applications.

DISCUSSION

Titanium's remarkable biocompatibility and resistance to corrosion have accelerated its growing popularity in medical and dental implant applications. In recent years, titanium has gained traction in prosthodontics as a cost-effective and biocompatible alternative for both removable and fixed prostheses. However, thorough assessments of long-term outcomes for titanium casting, joining, and porcelain bonding are essential before widespread applications. Titanium implants, whether composed of commercially pure titanium or alloys, have demonstrated efficacy in replacing missing dental components, due to the titanium oxide passive layer facilitating intimate tissue interaction.[6]

Structure of titanium:

Titanium, the ninth most abundant element in the earth's crust, is primarily extracted from mineral ores like rutile and ilmenite, using Kroll's process since 1936. It exhibits two crystal orientations: below 882°C, it forms a hexagonal close-packed alpha phase, while above 882°C, it adopts a body-centered cubic beta phase. Alloying with elements like aluminium, carbon, oxygen, nitrogen, manganese, chromium, iron, and vanadium stabilizes different phases of titanium at room temperature. With an atomic number of 22 and a mass of 47.88, titanium is a highly reactive transition element, with its electrons organized in four energy levels, each with 2, 8, 10, and 2 electrons. Each energy level is further divided into energy sublevels (s, p, d, and f). Titanium's strong reactivity stems from its lightly retained valence electrons.[7]

Classification of Ti Alloys

Titanium alloys are classified based on structure, strength, and grades.

Structure-Based Classification:

1. **Alpha Alloys:** Pure titanium alloys containing oxygen as the main alloying element. They have good corrosion resistance but limited by low strength.
2. **Near-Alpha Alloys:** Contain a mixture of alpha and beta phases, suitable for high-temperature applications with improved creep behavior.
3. **Beta and Near-Beta Alloys:** These alloys contain beta-stabilizing elements, allowing for heat treatment and high strength. Near-beta alloys maintain beta phase at room temperature for enhanced properties.
4. **Alpha and Beta Alloys:** Combining both alpha and beta phases, offering medium to high strength and excellent mechanical properties. Ti-6Al-4V is a widely used example.[8]

Strength-Based Classification: Titanium alloys are categorized based on yield strength:

1. **Low Strength:** Yield strength below 73 KSI (Kilo pounds per square inch), suitable for moderately strong applications.
2. **Moderate Strength:** Yield strength ranging from 73 to 131 KSI (500 to 900 MPa), used in valves, connecting rods, and similar structures.
3. **Medium Strength:** Yield strength from 131 to 145 KSI (900 to 1000 MPa), ideal for demanding applications in chemical and petroleum industries.
4. **High Strength:** Exhibiting tensile strengths from 145 to 174 KSI (1000 to 1200 MPa), suitable for aircraft components and medical implants.
5. **Very High Strength:** Alloys with tensile strengths exceeding 174 KSI (1200 MPa), used in aerospace, military, and high-pressure containers.

Grades of Ti Alloys: Commercially pure titanium and titanium alloys are categorized into various grades based on composition and properties:

- Grade 1 to 4: Pure titanium with varying strength and ductility, commonly used for corrosion resistance in chemical and marine industries.
- Grade 5 (Ti-6Al-4V): Most widely used alloy with high strength, heat resistance, and corrosion resistance, suitable for aerospace, automotive, and medical applications.
- Grade 23 (Ti-6Al-4V ELI): Extra low interstitial version of Ti-6Al-4V, offering higher ductility and fracture toughness, commonly used in biomedical implants and high-stress applications.

These classifications help in selecting the appropriate titanium alloy for specific industrial and biomedical applications.[9]

Properties of Titanium (Ti) and its Alloys:

I. Biocompatibility:

Titanium and its alloys exhibit excellent biocompatibility, avoiding inflammatory or allergic reactions. The formation of a passive oxide layer on the surface enhances its corrosion resistance. Low ion formation of titanium in aqueous environments minimizes reactivity with macromolecules, thus enhancing biocompatibilty. Therefore, titanium alloys are widely used in biomedical implants (e.g., dental, orthopaedic), artificial joints, cardiac devices, and more.[10]

II. Mechanical Properties

Yield strength of titanium ranges from 500 to 1000 MPa for biomedical titanium alloys. The factors contributing to high tensile strength include grain size reduction, dislocation networks, and solid solution strengthening.[11] Titanium alloys with 25-75% zirconium exhibit 2.3-3 times higher tensile strength than pure titanium.[12] Titanium alloys also have lower Young's moduli compared to stainless steel and Co-Cr-Mo alloys. Beta-type titanium alloys offer lower modulus and are preferred for biomedical applications. Low Young's modulus alloys, such as Ti-13Nb-13Zr, Ti-12Mo-6Zr-2Fe have been developed to match bone modulus.[13] The fracture toughness of titanium alloys is inversely related to tensile yield strength.[14] High fracture toughness is essential for preventing prosthesis fracture.[15] Electron beam melting (EBM) and Hot Isostatic Processing (HIPing) have proven to improve fatigue endurance limit of titanium. Hydrogen sintering and phase transformation (HSPT) and laser shock peening (LSP) also enhance fatigue resistance.[16]

III. Chemical Properties

With atomic number 22 and weight 47.90, titanium exhibits chemical behaviour akin to silica and zirconium. Titanium's primary oxidation state is 4+, though states 3+ and 2+ exist. It forms dioxide (TiO2) when heated in air and reacts with concentrated acids to produce trichloride. Titanium dioxide serves as a white pigment in outdoor paints and possesses bactericidal properties. Alkaline earth titanates, including barium titanate, exhibit significant dielectric properties. Surface modifications like etching, annealing, and coating enhance titanium's properties, such as roughness and wettability, making it biologically favorable for various applications.[17]

IV. Osseointegration:

Osseointegration, the direct structural and functional connection between living bone and titanium implants, is crucial for successful oral rehabilitation.[18] Titanium alloys, particularly cpTi and Ti-6Al-4V, facilitate osseointegration by promoting bone growth due to their bioactivity. The process relies on a thin interfacial zone where bone cells release growth factors, initiating new bone production.[19] Surface roughness plays a pivotal role in osseointegration, with methods like plasma spraying, grit blasting, acid etching, and anodization enhancing implant surface texture. Surface characteristics, including wettability and charge, influence protein adsorption and cell adhesion, while nanoscale topography further enhances cell proliferation and bone-to-implant contact. These surface modifications aim to optimize biocompatibility and improve the performance of titanium implants for oral rehabilitation.[20]

Jemat et al.[21] carried out a study to evaluate the effect of surface modifications on dental implants and it was found that among all the surface treatments, acid etching and plasma spray coating were the most preferable modes. These surface modifications did enhance the osseointegration and improved the biomechanical fixation of titanium implants.

Manufacturing Of Titanium and Titanium Dental Implants

Casting, particularly through arc melting, stands out as a vital step in manufacturing, demanding precise control over inert gases due to titanium's exceptionally high reactivity and melting point. It's imperative to maintain an inert atmosphere during melting and casting to prevent oxidation, necessitating meticulous attention to detail even in the composition of the mold's oxide component. Investment casting is another crucial technique, enabling the fabrication of intricate geometries with high dimensional accuracy, thereby significantly reducing machining costs. [22] Subtractive techniques such as micro-milling play a pivotal role, particularly in shaping micro-scale devices where titanium's remarkable strength and low density are highly advantageous. Despite its low machinability, micro-milling provides intricate shaping capabilities, along with careful consideration of tool features to optimize chip formation, cutting force, and surface finish quality.[23] Additionally, additive manufacturing methods like 3D printing are gaining traction due to their ability to rapidly produce implants with superior mechanical properties. By precisely controlling variables such as porous scaffolds, density, and pore size, 3D printing ensures optimal implant quality, making it an increasingly preferred method for manufacturing titanium and titanium alloy implants. Its ability to replicate exact shapes and dimensions while regulating the quality of different living tissues further cements its appeal.[24]

Biomedical Applications of Titanium

Applications in Medicine: Titanium alloys are widely used in medicine for implants like hip and knee joints, bone plates, and cardiac prostheses. However, concerns about toxicity from aluminum and vanadium in some alloys have led to the development of safer alternatives like Ti6Al7Nb and Ti13Nb13Zr.

Removable Implants in Orthopedics: Internal fixation devices sometimes need removal, which can cause complications. Titanium alloys like Ti-Zr-Nb and Ti-Zr-Al-V prevent calcium phosphate precipitation, reducing the risk of bone fracture during removal.[25]

Applications in Prosthodontics:

Implant Dentistry: Titanium's mechanical properties and biocompatibility make it ideal for dental implants. Though Ti-6Al-4V is common, concerns about vanadium and aluminum have increased the use of commercially pure titanium.[26] The conical–cylindrical and conical–hexagonal shape designs are the most commonly used implants and can vary in structural characteristics, such as 4–10 mm in length by 1 to 2 mm in diameter. Mini hexagonal implants with a length of 4–6 mm are the ones with the highest success percentage and the shortest osseointegration time. [27] Healing abutments, which primarily serve the purpose of promoting healing at the surgical site, are usually made from titanium and its alloys. Gubbi et al. [28] have reported the use of titanium in various types of abutments like locator abutments, low profile abutments, titanium temporary abutments and hex-lock contour abutments.

Patient-Specific Titanium Meshes: Titanium meshes aid in bone regeneration and cranioplasty, reducing surgery complexity and improving aesthetic results. Prefabricated patient-specific titanium implants reduce surgical complexity, decrease the operative time, drastically minimize the risk of contamination, and result in better aesthetics. [29] Hartmann et al.[30] have reported the use of titanium mesh in skull base surgery, for reconstructive purposes. It can be used to restore the orbital floor, the frontal sinus wall, and other different deformities of the skull. No artefacts on radiographs are found, and it is easily adjusted to complex structures. Since mesh is flexible, it can be fastened with titanium screws, thereby easily covering the defects.

Titanium Plates: Titanium plates are used for bone fixation after fractures or osteotomies, offering solid fixation with reduced healing time. 3D-printed miniplates offer stable fixation with fewer complications compared to traditional methods. The advantage of these plates is that they induce sufficient strength and rigidity to enable bony union, extremely low tendency to produce foreign body reactions, high biocompatibility and ease of manipulation. [31]

Complete Denture Framework: Titanium alloy frames for complete dentures provide strength and durability, with reduced bacterial growth compared to other materials.[32] Zhang et al.[33] reported the digital fabrication of complete denture using pure titanium alloy for baseplate fabrication. The procedure used is selective laser melting (SLM). Pure titanium alloys provide better fracture resistance. Wang et al. [34] found that SLM fabricated pure titanium specimens had better bacterial resistance than casting or milled titanium because the SLM fabricated specimen had a higher titanium dioxide percentage, and the main function of titanium dioxide is to provide resistance to bacterial adherence because of its passive layer.

Removable and Cast Partial Denture Frameworks: Titanium and its alloys offer superior mechanical properties for removable dentures, but casting can be challenging. CAD/CAM technology improves fabrication precision. Every component of the RPD can be crafted using CAD/CAM technology, with the exception of the clasps, which are typically cast and then laser-welded onto the framework. Ti-6Al-7Nb major connector exhibit rigidity similar to conventional Co-Cr connector. Ti-6Al-4V exhibit superplastic forming ability, thereby making it useful for fabricating the palatal plate of maxillary major connector. Since the titanium plates are very thin and of uniform thickness, most patients find them to be extremely comfortable. Compared to the cast metal plates, titanium plates have better fit, owing to the superelastic properties of titanium. [35]

Titanium Frameworks in Implant-Supported Prostheses: Titanium frameworks, fabricated using CAD/CAM techniques, offer improved fit and strength for implant-supported restorations. Frameworks fabricated using these techniques offer avoidance of residual stresses, and a very minimal amount of local strain, thereby preventing the fracture of the prosthesis. [36]. Paniz et al. [37] conducted a study to compare the fit of milled vs cast frameworks and it was found that titanium frameworks weighted less than traditional cobalt-chromium frameworks.

Titanium Base Abutments in Implant Prosthodontics: Titanium base abutments, with custom designs and laser welding, provide stability and durability for implant-supported restorations. Prefabricated titanium abutments are commonly used due to their simplicity and cost-effectiveness, particularly in cases suited for cement-retained restorations and ideal implant placement scenarios. However, their applicability may be limited to cases where the edentulous area's depth, emergence profile, and diameter align with standard dimensions. To address the shortcomings of prefabricated abutments, especially in off-axial implants with buccally emerging screw access, custom abutments are recommended. These can be either cast from metal alloys or milled using CAD/CAM technology, offering superior strength, durability, and versatility for both cement- and screw-retained prostheses. Custom abutments enable the fabrication of fixed prostheses with precise thickness, often incorporating titanium base abutments with specific geometries stored in CAD/CAM systems for efficient restoration fabrication. After milling and undergoing necessary processing steps like sintering or crystallization, the restoration is externally cemented or bonded to the titanium base before insertion onto the dental implant.[38]

Customized zirconia abutments with titanium inserts offer a solution to certain challenges associated with titanium abutments. While titanium is known for stability and promoting gingival health, its use in thin peri-implant mucosa can sometimes result in visible metal parts through the tissue. Zirconia abutments, on the other hand, have gained popularity due to their excellent material properties and biocompatibility, especially in aesthetic areas.

To enhance the mechanical performance of zirconia abutments, titanium inserts are incorporated. These inserts, attached to the bottom of the zirconia abutment, establish titanium-to-titanium contact with the implant, ensuring proper force distribution along the internal connection. This configuration addresses mechanical limitations associated with zirconia, such as flexural strength, fatigue load, and fracture resistance.[39]

Compared to one-piece zirconia abutments, the mechanical stability of titanium insert-reinforced zirconia abutments is significantly improved. The titanium insert provides higher flexural strength, contributing to the overall durability of the restoration. It's important that the axial height of the titanium insert is designed to be at least 3 mm to optimize fracture strength and ensure the long-term stability of implant-supported fixed prostheses featuring titanium insert-reinforced zirconia abutments.[40]

Other Dental Applications:

Nickel-titanium rotary instruments are used for endodontic treatments, while orthodontic wires and brackets made from titanium alloys provide flexibility, biocompatibility, and reduced friction.[41]

In summary, titanium's versatility and biocompatibility make it invaluable in both medical and dental fields, offering solutions for a wide range of applications.

CONCLUSION

Titanium and its alloys are pivotal in medicine and dentistry due to their biocompatibility, strength, and corrosion resistance. In dentistry, titanium plays a crucial role in implants, crowns, bridges, and dentures, ensuring durable and functional restorations. Ongoing research enhances titanium's properties, driving innovation in prosthodontics and promising improved patient outcomes. Additionally, advancements in nanotechnology and surface modification techniques hold potential for further breakthroughs, highlighting titanium's enduring legacy in biomedical applications.

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