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Original Article

Types and biological effects of titanium alloys in prosthodontics

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Abstract

Recent EU regulations recommend restriction of the use of medical devices in which cobalt content exceeds 0.1%. Commercially pure titanium (cpTi) and titanium alloys appear to be excellent alternatives to cobalt-based alloys in the fields of implantology and prosthodontics. The narrative review summarizes the structure and types of titanium alloys and the methods of their processing. The high biocompatibility of titanium is explained in terms of corrosion, ion release, and interaction with the biological environment. An analysis of existing studies on the mechanical properties of titanium prosthetic restorations is presented, and future perspectives are outlined.

Keywords

biocompatibility, corrosion, prosthetic restorations, titanium alloys

Structure and types of titanium alloys

Recent EU regulations recommend restriction of the use of medical devices in which cobalt content exceeds 0.1%. [1] As cobalt constitutes 30%–60% of the composition of commonly used cobalt-chromium dental alloys, new biomaterials with similar properties should replace these alloys. Commercially pure titanium (cpTi) and titanium alloys appear to be excellent alternatives to cobalt-base alloys in the fields of implantology and prosthodontics.[2-4] Approximately 2% of titanium produced currently is used for medical applications. Titanium medical devices possess high corrosion resistance, acceptable mechanical strength, excellent biocompatibility, and modulus of elasticity close to that of the bone.[5]

CpTi is classified into four grades based on the levels of impurities: iron, oxygen, and nitrogen. The four grades of cpTi exhibit varying strengths, with a correlation between tensile strength and oxygen content.[6] Titanium is an element which undergoes allotropic transformation of the crystalline lattice. At room temperature, a hexagonal α-structure is present, which transforms into a body-centered cubic β-structure with increasing temperature up to 883°C. Regarding the crystalline structure, titanium alloys are divided into five classes – α, near α, α+β, near β, and β. By adding different elements (O, V, Al, Ta, N, C, Nb) in the alloy composition, the crystalline structures can be modified and stabilized.[5] The American Society for Testing and Materials (ASTM) has established standards specifying requirements for the composition of titanium alloys based on their intended use, classifying them into up to 38 grades.[7-10]

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Methods of fabrication of titanium devices

According to Lautenschlager and Monaghan[11], titanium and titanium alloys can be used not only in implantology but also in prosthodontics for fabrication of prosthetic restorations. However, the characteristics of these materials require specific casting and melting conditions, as well as the use of specially developed refractories and ceramic faceting tables.[11] As titanium is prone to oxidation at high temperatures, the casting and melting processes should be performed in the presence of inert gases like argon. Due to its low density, casting must be performed under pressure higher than atmospheric pressure. Since the affinity to oxygen may lead to reaction with the SiO_2, which is the main component of the conventional investment materials, different types of investment materials must be applied with MgO, Al_2O_3, or ZrO_2 used as a refractory part.[12]

The development of computer-aided design/computer-aided manufacturing (CAD/CAM) and additive manufacturing techniques (AM, 3D printing) has revolutionized dentistry by transforming clinical and laboratory practices and offering numerous advantages: a wider range of fabrication methods and materials, the ability to create devices with complex geometries, reduced manufacturing time, and minimized material waste.[13,14] Additive manufacturing facilitated the implementation of titanium and its alloys in everyday dental work. It is considered that titanium and titanium alloys are perfect materials for 3D printing in the field of implantology and maxillofacial reconstructions.[15] Selective laser melting (SLM), direct metal laser sintering (DMLS), electron beam melting (EBM), and laser metal deposition (LMD) are some of the commonly used additive techniques for processing titanium alloys.[16] SLM and DMLS utilize fine metal powders, placed in a thin layer over the building platform. A laser beam melts and fuses the particles into a shape determined by the 2D section of the designed object. The platform then moves vertically, a new powder layer is applied, and the laser creates the next 2D section. In the process of EBM electron beam energy is used to melt and fuse the metal powder in the desired shape. In the LMD technique, the metal powder is injected into the area of focus of a laser beam, which creates the object in layers like in the aforementioned methods.[17] Another method offering 3D printing of titanium restorations is binder jetting (BJ). This technique utilizes a liquid binding agent which is placed onto the layer of powder alloy according to the 2D-section of the CAD file. The platform is then moved for the creation of the next layer. The resulting 'green' object is then post-processed and sintered to achieve optimal physical and mechanical properties. The disadvantages of BJ are shrinkage after sintering and the lengthy post-processing time.[18]

Biological effects of titanium

The excellent corrosion resistance of titanium and its alloys plays a crucial role in the host response to titanium medical prosthesis. The resistance to corrosion is due to the fast spontaneous formation of stable surface oxide layer of TiO_2. Nevertheless, when this passive layer is compromised, metal ions and particles are released into the surrounding tissues and biological fluids. The stability of the passive layer depends on the electrode potential and the acidity of the medium, which may be modified by the presence of oxygen, some cell types, bacteria, inflammatory diseases (gingivitis, periodontitis), substances like amino acids, lipopolysaccharides (result of bacterial metabolism), and proteins.[19] It may also be distorted by mechanical forces (tribocorrosion). Some specific conditions in the oral cavity also contribute to potential titanium release. Studies show that corrosion properties of titanium dental alloys may be affected by mechanical tooth brushing, use of fluor-containing mouthwashes and toothpastes, intake of soft drinks and snacks.[20-22]

Chemical and physical properties of dental materials are tightly correlated with the production of reactive oxygen species (ROS) and reactive nitrogen species (RNS).[23] As a result of corrosion, biological interactions, and metal degradation, ions and particles may be released from dental restorations, leading to changes in local and systemic oxidative stress levels and potential cellular disturbances.[24-26] Although uncommon, titanium hypersensitivity has been described and should not be underestimated.[27,28]

Although titanium is detected in the tissues surrounding the titanium implants, its toxicity is exceptionally low. Hanawa[24] explains the excellent biocompatibility of titanium (considered an inert material) with the fast interaction of the emitted titanium ions with hydroxide ions and other anions, leading to the formation of oxides, hydroxides, and salts, which hardly react with biomolecules and take part in the repassivation of the metal surface.[24]

Methods for properties modification – alloy composition changes, surface treatment

The modulus of elasticity of cpTi is close to, but not equal to, the elastic modulus of the bone. This property might lead to mechanical stress in the bone-implant interface and treatment failure. This is one of the main reasons for the invention and application of titanium alloys that surpass the properties of the pure titanium. Another option for properties modification is application of surface treatment methods for titanium devices.[29] Ti 6Al-4V is one of the most used titanium alloys in the field of orthopedic medicine because of its high corrosion resistance and mechanical properties. Nevertheless, there are studies that raise some concern about the biological effects of the components. Aluminum ion release may cause cytotoxic reactions and neurological changes, such as Alzheimer's disease[30], while vanadium is considered to have cytotoxic and carcinogenic effects.[5] New types of titanium alloys are created in which these elements are replaced by niobium, tantalum, zirconia, etc.[31]

To lower the elasticity modulus and reduce the amount of potentially toxic elements, new biocompatible β-titanium alloys have been designed with stabilizing elements such as tin (Sn), zirconia (Zr), tantalum (Ta), silicon (Si), and molybdenum (Mo) to keep the β-structure at room temperature. Compared to α-alloys these β-alloys show higher biocompatibility, greater similarity of elasticity modulus to that of the bone, and supreme mechanical properties.[32,33] The addition of copper (Cu) in the alloy composition increases its antibacterial properties, which may contribute to the good prognosis of implant treatment.[34]

Titanium alloy properties can be modified through surface treatment. Bone osseointegration may be improved by coating titanium implant surface with calcium hydroxide nanoparticles.[35] Studies show that strontium-containing coatings produced by micro-arc oxidation and incorporation of zinc on the titanium implant surface lead to a better biological response.[36,37] Surface plasma treatment of dental implants increases hydrophilicity and accelerates osseointegration.[38]

Titanium and titanium alloys in prosthodontics

Nowadays cpTi and titanium alloys are widely used for fabrication of scaffolds and implants in orthopedics, maxillofacial surgery, and dentistry because of their high biocompatibility and favorable host response.[15,39] In prosthodontics, titanium implant-supported frameworks may be cast, milled, or 3D printed, providing precise fit and patient satisfaction of the treatment.[40]

Removable dentures made of titanium offer a combination of high strength and low weight.[41] Although lower than in cobalt-chromium, the fatigue resistance and the retention force of titanium clasps are clinically acceptable and higher than the ones of PEEK clasps.[42] When the metal framework is produced by SLM, titanium clasps exhibit less deviation than cobalt-chromium clasps.[43] To improve the retention between the metal substrate and the acrylic denture base material, additional treatment may be required (sandblasting of the metal surface with Al_2O_3 particles and application of a primer).[44]

Titanium alloys appear as an alternative to cobalt-chromium alloys for fixed prosthetic restorations, as the internal and marginal fit of titanium restorations are comparable to that of cobalt-chromium.[45] However, fusing porcelain to titanium framework requires specific treatments and an appropriate choice of ceramic materials. The temperature increase during sintering may lead to creation of thick and brittle oxide layer, causing cohesive fractures in the restoration. According to the recommendations of producers, bonding agent must be applied and low-fusing porcelain masses with coefficient of thermal expansion corresponding to that of titanium must be used.[46] The bond strength between the alloy and lithium silicate ceramics may be increased by etching with hydrofluoric acid and by sandblasting of the metal surface.[47]

The electronic search we did for relevant contemporary information in the PubMed database indicates that the application of titanium alloys in conventional removable and fixed prosthodontics is insufficiently studied, confirming the significance of this review and literature analysis.

Conclusion

Considering the high biocompatibility and appropriate mechanical properties, cpTi and titanium alloys may successfully replace cobalt-based dental alloys, thus widening their application not only in the field of dental implantology but also in most of the prosthetic clinical cases. However, the unique characteristics of these alloys require specific laboratory equipment and post-processing. A working hypothesis for the successful clinical implementation of titanium alloys in prosthodontics in Bulgaria could guide future research.

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