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Review

Is there scientific evidence favoring the substitution of commercially pure titanium with titanium alloys for the manufacture of dental implants?

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ABSTRACT

The development of Ti alloys to manufacture dental implants has emerged in recent years due to the increased failure of commercially pure titanium (cpTi) implants. Thus, this study reviews existing information about the mechanical, chemical, electrochemical, and biological properties of the main Ti alloys developed over the past few years to provide scientific evidence in favor of using Ti-based alloys as alternative to cpTi. Ti alloys may be considered viable substitutes in the fabrication of dental implants. Such evidence is given by the enhanced properties of alloys, such as a low elastic modulus, high tensile strength, satisfactory biocompatibility, and good corrosion and wear resistances. In addition, Ti alloys may be modified at the structural, chemical, and thermomechanical levels, which allows the development of materials in accordance with the demands of several situations encountered in clinical practice. Although several *in vitro* studies have established the superiority of Ti alloys over cpTi, mainly in terms of their mechanical properties, there is no scientific evidence that supports the total replacement of this material *in vivo*. This review demonstrates the superiority of β-type alloys. However, it is evident that *in vivo* studies are encouraged to test new alloys to consolidate their use as substitutes for cpTi.

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1. Introduction

The durability of rehabilitative treatments depends on the availability of materials capable of minimizing the risk of mechanical failure, especially in applications involving the treatment of large defects subject to high loads or where it is necessary to reduce the implant dimensions [1]. Progress in this area has achieved improvements in treatment performance and longevity; nevertheless, failures still occur [2]. In order to overcome these failures, dental implant materials should present high fatigue strength, low elastic modulus, high strength [3], and good corrosion resistance and biocompatibility [4].

Commercially pure titanium (cpTi) is the material of choice for the manufacture of dental implants [5]. However, its use is limited in areas subjected to high wear and tensile and fatigue strength [2,6,7]. Because Ti is a relatively soft material [8], fatigue may occur, particularly when it is used in small-diameter implants, which must fulfill high requirements for mechanical stability to avoid overload and implant fracture [9]. In addition, high-elasticity modulus and difficulty in improving its mechanical properties without any reduction in biocompatibility have been considered characteristics that limit the use of cpTi as a material of dental implants [4]. The use of Ti alloy made by grinding Ti with other metals is an alternative option to obtain better mechanical properties [8].

Several elements may be combined with Ti, resulting in alloys with distinct properties and patterns closer to the ideal for use as dental implants. Ti-6Al-4V alloy is widely used owing to its excellent mechanical performance [2]. On the other hand, this alloy showed negative effects on cell viability by the release of Al and V [10], with a consequent adverse influence on implant biocompatibility [11]. Indeed, Al has been linked to significant neurotoxic effects, especially when considering reports of its association with Alzheimer's disease, bone fragility [12], and potential causes of local inflammation [13]. These reports have discouraged the use of Ti-6Al-4V and stimulated the development of alloys free of toxic elements that are inert in the oral environment.

To extend their clinical application, experimental alloys must exhibit satisfactory mechanical properties, with sufficient strength and stability in a corrosive environment, besides being biocompatible and safe for *in vivo* use [14,15]. Ti alloys have proven to be of great interest for biomedical applications due to their excellent strength and superior biocompatibility [3] associated with properties such as high tensile strength, good corrosion resistance [16], and elastic modulus comparable to that of bone tissue [17,18]. These outstanding properties have pointed to Ti alloys as viable options to be used as an alternative to cpTi in the manufacture of dental implants, and in many cases, for use as the first choice in treatment [19].

Although several alloys are designed for biomedical applications, many studies are inconclusive concerning the possibility of using these new materials as substitutes to cpTi. In addition, few studies have tested experimental alloys *in vivo* to consolidate their use. In this article, we provide a summary of several relevant aspects of Ti alloys for use as dental implants. Existing information about the mechanical, chemical, electrochemical, and biological properties of the main alloys developed over the past few years is deeply reviewed to provide scientific evidence in favor of using Ti-based alloys as alternative of cpTi with its alloys in the clinical scenario.

2. Classification of Ti alloys

Ti can take on two different crystal forms in a temperature-dependent manner. The α phase has a hexagonal closed-packed (HCP) structure and is stable from room temperature to 882 °C. The β phase has a body center cubic (BCC) structure and is stable at temperatures higher than those mentioned above [8,19,20]. Ti also presents metastable phases, such as the hexagonal martensite α' and orthorhombic α'' phases [21]. The transition temperature between the α and β phases can be changed by combining elements with Ti, which consequently modifies its microstructure. Besides the constitution of the alloy, the processing approach and heat treatment conditions affect the material's microstructure [22].

The microstructure of Ti alloys is defined according to the type and concentration of the alloying elements, as well the crystalline phases present at room temperature [20,23]. Elements that may constitute Ti alloys are classified into three categories: α-stabilizers (Al, O, N, C) tend to stabilize the α phase by increasing the transition temperature; β-stabilizers (Mo, V, Fe, Cr, Ni, Co, Nb) depress the transition temperature by stabilizing the β phase; and elements such as Zr and Sn exhibit no effect on the stability of any phase, being considered neutral elements [11,19]. Table 1 summarizes this information for better understanding. To understand such mechanism, the phase diagram of Ti as a function of stabilizers constituents is shown in Fig. 1. The effect of elements addition at the transition temperature between α and β phases can be clearly seen.

Depending on the proportion of each phase, Ti can be further classified as near α, α, α + β, near β, and β phases [21]. The near-α alloys contain approximately 1–2% of β-stabilizers and approximately 5–10% of β phases; alloys that present in their constitution higher amounts of β- stabilizers, resulting in 10–30% of β phases in the microstructure, are classified as α + β alloys; the near β and β alloys have higher amounts of β-stabilizers and predominantly β phase in their microstructures [19]. Fig. 2 shows the relationship between the concentration of stabilizer elements incorporated into the Ti and its microstructural phases.

It is known that microstructure has a great influence on the physical and chemical properties of the material [22] and is widely affected by the volume fraction, morphology, distribution, and size of the α phase precipitates within the matrix [24]. Knowing the elements that influence the microstructure of Ti and understanding how this relationship occurs has driven many researchers to incorporate elements to pure Ti to produce implants with greater performance than those made of cpTi.

The addition of V and Al to Ti forming Ti-6Al-4V, for example, was considered to provide a biphasic structure (α + β) because of the stabilizing effects of α and β. The alloys that exhibit α + β structure are characterized by higher strength, higher ductility and higher low-cycle fatigue [19]. Furthermore, alloys containing Al provide a high rate of solid solution hardening to the Ti matrix [14], with Ti-6Al-4V being the most common Ti alloy used for biomedical applications where high strength is required [25].

Similar to Al, Zr and Bi have been used to induce a solid solution hardening effect [7,26,27]. When Zr is cast only with Ti, it can form α alloys of various proportions, which usually increase the mechanical strength (such as tensile strength, hardness and flexural strength) and improve the corrosion potential and wear resistance of Ti [21]. In contrast, β alloys have in their constitution β-stabilizers acting as grain refiners [3]. Among them, Nb, Mo and Ta have received emphasis for forming β alloys characterized by a combination of improved mechanical properties and excellent biocompatibility [7,22]. They also present low elastic modulus [22,28], superior corrosion resistance [22], good plasticity, high yield strength [28], hardenability, fracture toughness, and reasonable ductility [24]. These characteristics have made them the most promising alloys for the manufacture of implants [20,22].

Table 1
Main components of Ti alloys and their influence on the transition temperature and Ti matrix.

	Element	Influence on the transition temperature	Main effect on Ti matrix
α-stabilizer	Al, O, N, C	Increase	Hardening
β-stabilizer	Mo, V, Fe, Cr, Ni, Co, Nb	Decrease	Grain Refiners
Neutral	Zr and Sn	No significant effect	Hardening