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Development of binary and ternary titanium alloys for dental implants

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ABSTRACT

Objective. The aim of this study was to develop binary and ternary titanium (Ti) alloys containing zirconium (Zr) and niobium (Nb) and to characterize them in terms of microstructural, mechanical, chemical, electrochemical, and biological properties.
Methods. The experimental alloys — (in wt%) Ti–5Zr, Ti–10Zr, Ti–35Nb–5Zr, and Ti–35Nb–10Zr — were fabricated from pure metals. Commercially pure titanium (cpTi) and Ti–6Al–4V were used as controls. Microstructural analysis was performed by means of X-ray diffraction

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and scanning electron microscopy. Vickers microhardness, elastic modulus, dispersive energy spectroscopy, X-ray excited photoelectron spectroscopy, atomic force microscopy, surface roughness, and surface free energy were evaluated. The electrochemical behavior analysis was conducted in a body fluid solution (pH 7.4). The albumin adsorption was measured by the bicinchoninic acid method. Data were evaluated through one-way ANOVA and the Tukey test ($\alpha = 0.05$).

Results. The alloying elements proved to modify the alloy microstructure and to enhance the mechanical properties, improving the hardness and decreasing the elastic modulus of the binary and ternary alloys, respectively. Ti–Zr alloys displayed greater electrochemical stability relative to that of controls, presenting higher polarization resistance and lower capacitance. The experimental alloys were not detrimental to albumin adsorption.

Significance. The experimental alloys are suitable options for dental implant manufacturing, particularly the binary system, which showed a better combination of mechanical and electrochemical properties without the presence of toxic elements.

1. Introduction

Commercially pure titanium (cpTi) has been widely used as the main biomaterial for the manufacture of dental implants [1,2]. Nevertheless, like any other material used in physiological conditions, it is exposed to mechanical and biological factors [3] that may impair implant survival and long-term treatment success. In this context, alloys have been considered to be the treatment of choice [4], due to their improved properties, which allow for the development of materials according to clinical demands [5].

The Ti–6Al–4V alloy is widely used in the replacement of cpTi in situations where high strength is required [6] because of its excellent mechanical performance [2]. However, this material has been shown to be biomechanically incompatible owing to its higher elastic modulus compared with that of bone. Further, Ti–Al–V has been associated with the release of V into the blood and urine [7], initiation of the inflammatory cascade leading to osteolysis [8,9], neurotoxic effects, negative cell viability response, and, consequently, an undesirable outcome for implant biocompatibility with ion release [10–12]. In addition, Al has been shown to be present in brain tissue of patients with Alzheimer's disease [13].

Metal ions and debris released from implant materials are strongly associated with implant corrosion tendencies in physiological conditions [14,15]. Besides affecting the implant's biocompatibility, the corrosion phenomenon changes the implant's mechanical properties and affects the bone through the abrasion and wear regimes [16]. Thus, implant materials must not only fulfill mechanical requirements but also offer appropriate biological and electrochemical properties.

Experimental Ti alloys without the presence of Al and V are being processed and studied to achieve these properties [17]. Zirconium (Zr) and niobium (Nb) elements have attracted much special attention [18]. Zr acts as a solid-solution strengthening component when alloyed with Ti [1,19]. Ti–Zr alloys present a predominantly α-crystalline structure, which guarantees increased mechanical resistance and excellent electrochemical behavior [1,20]. In contrast, Nb is a β-stabilizer that is added to Ti to create $\alpha+\beta$ and β alloys, which have demonstrated more promising properties for biomedical use [21], such as an excellent combination of low elastic modulus and high tensile strength [22,23]. In addition, the Ti–Nb–Zr alloy has shown non-toxicity toward osteoblastic cells, no allergy-related problems, and excellent biocompatibility [18].

To extend the clinical application of implants, it is necessary to develop new alloys that are sufficiently strong, present low elastic modulus, and are stable in a physiological environment. As mentioned above, Ti–Zr and Ti–Nb–Zr alloys appear to be promising candidates for dental implant applications. Extensive studies have been conducted with cpTi and Ti–6Al–4 V [24–28], but studies with Ti alloys containing Nb and Zr are limited. Thus, the aim of the current study was to characterize the microstructure and mechanical, chemical, and electrochemical properties of binary and ternary Ti alloys containing Zr and Nb and to conduct a comparison with the materials that are widely used for dental implants: cpTi and Ti–6Al–4V alloy. The biological aspects of such alloys were investigated by means of a protein adsorption assay.

2. Materials and methods

The experimental design of this study can be seen in Fig. 1. Two control groups were considered: cpTi and Ti–6Al–4V alloy discs (Mac-Master Carr, Elmhurst, IL, USA) 10 mm in diameter and 2 mm in thickness. These materials were chosen because they are widely used in the manufacture of dental implants.

2.1. *Fabrication of experimental alloys*

The experimental alloys (in wt%) (Ti–5Zr, Ti–10Zr, Ti–35Nb–5Zr, and Ti–35Nb–10Zr) were melted from pure metals (Ti, Nb, and Zr presented degrees of purity equal or superior to 99.0%) (Sigma–Aldrich, St. Louis, MO, USA) in an arc-voltaic furnace with a water-cooled copper crucible under an argon atmosphere. The ingots were flipped and re-melted five times to ensure homogeneity of the samples [1,29,30]. The Ti–Nb–Zr ingots were encapsulated in quartz tubes, heat-treated at 1000 °C for 8 h, and furnace-cooled [29,30]. All ingots were