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Mechanical properties, surface morphology and stability of a modified commercially pure high strength titanium alloy for dental implants

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ABSTRACT

Objective. Commercially pure titanium (cp Ti) and Ti–6Al–4V (Ti G5) alloy have limitations for biomedical application, due to lower mechanical strength and the possibility of ion release, respectively. The purpose of this work was to compare the properties of a modified cp Ti grade 4 (Ti G4 Hard) with those of available cp Ti and Ti G5 alloys.

Methods. Bars, discs and dental implants made with Ti G2, G4, G5 and G4 Hard were used. Mechanical tests (tension, compression, hardness and torque) and roughness measurements were performed. Clinical trials were used to evaluate the biological behavior of dental implants made with Ti G4 Hard and Ti G4.

Results. The results of the mechanical tests showed that the mechanical strength of modified Ti G4 is higher than that of Ti G2, G4 and G5. Scanning electron microscopy analysis showed that modified Ti G4 after etching has better surface morphological features than conventional cp Ti and Ti G5. The clinical performances of Ti G4 and Ti G4 Hard were similar.

Significance. The improvement of the mechanical properties of modified Ti G4 means that Ti G5 can be safely replaced by Ti G4 Hard without compromising the fracture resistance, with the advantage of not releasing toxic ions.

1. Introduction

The selection of materials for dental implants is based on mechanical properties, chemical properties and biocompatibility. Regardless of the role and place of application of dental implants, the materials should have good corrosion resistance, biocompatibility and be free of toxic elements. Currently, dental implant manufacturers use commercially pure titanium and titanium alloys with a treated surface in order to optimize the contact between alveolar bone and the device surface. This histologic interaction is called osseointegration [1,2].

Technical Standard ASTM F67 classifies cp Ti for medical applications in four grades, G1–G4 (see Table 1). However, cp Ti is not used in medical applications that involve high stresses, such as orthopedic prostheses. In these cases, Ti

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Table 1 – Standard ASTM number, chemical requirements (max mass%), tensile strength (TS), yield strength (YS), modulus of elasticity (*E*) and Brinell hardness (HB) of cp Ti, Ti alloy G5 and bone properties. Based on Technical Standards ASTM F67 and ASTM F136.

Ti grade	ASTM	O	Fe	H	C	N	Ti	TS (MPa)[a]	YS (MPa)	E (GPa)	HB
Ti grade 1	F67	0.18	0.20	0.015	0.08	0.03	Balance	240	170	100	120
Ti grade 2	F67	0.25	0.30	0.015	0.08	0.03	Balance	345	275	100	160
Ti grade 3	F67	0.35	0.30	0.015	0.08	0.05	Balance	450	380	100	200
Ti grade 4	F67	0.40	0.50	0.015	0.08	0.05	Balance	550	483	102	250
Ti grade 5[b]	F136	0.13	0.25	0.012	0.08	0.05	Balance	860	795	115	
Cortical bone								186		5–30[c]	

[a] Mechanical properties requirements for annealed wire with diameter higher than 3.18 mm.
[b] The compositional requirement Ti G5 shall meet the following: Al: 5.5–6.5 and V: 3.5–4.5.
[c] The bone modulus depending on the type of the bone and the direction of measurement.

G5 (a Ti–6Al–4V alloy) is the preferred choice due to its high mechanical resistance, which ensures load transmission to bone tissues over a long time, which is necessary when damaged hard tissues are replaced by prostheses. [3]

The ASTM F136 Standard specifies the requirements of Ti G5 (Ti–6Al–4V) for biomedical applications. This alloy has good mechanical properties, but exhibits a possible toxic effect from released vanadium and aluminum [4]. For this reason, vanadium and aluminum free Ti alloys have been proposed for biomaterials applications. All materials listed in Table 1 are used in dental implants. The disadvantage of Ti grade s 1–4 (cp Ti) for dental implants include higher Young modulus, relatively low mechanical strength, poor wear resistance and difficulty to improve the mechanical properties without reducing biocompatibility. The mechanical properties of unalloyed Ti are determined by the levels of interstitial solutes (N, O and C). Although the interstitial solutes increase the strength of Ti, they are deleterious to toughness. When high toughness is desired, the unalloyed Ti is produced with extra-low interstitial (ELI). ELI titanium alloy containing small amounts of oxygen, carbon, nitrogen and hydrogen as interstitial solutes (Table 1). Pure Ti can be cold-rolled at room temperature until 90% reduction in thickness without cracking. Such extensive deformability is unusual for HCP metals, and is related to the low *c*/*a* ratio of Ti [5]. HCP metals including cp Ti have three independent slip systems, which is insufficient to deform only by slip. Ti deformation twinning should be accompanied by slip for the HCP metals to sustain large deformation without cracking. Ahn et al. [6] analysed the effect of deformation twinning on the strain hardening behavior of cp Ti. The strain hardening rate of titanium can be divided into three stages. In the first stage, the strain hardening rate decreases as the strain increases due to from easy glide. Following the first stage, however, a sudden increase in the strain hardening rate is observed in the second stage. The second stage results from the generation of deformation twinning. The strain hardening rate decreases again as the strain increases in the third stage due the dynamic recovery [6,7].

Since there is a direct relation between interstitial content and mechanical strength, Ti G1 has the lowest mechanical strength, while Ti G4 has the highest strength (Table 1). Table 1 shows that the tensile strength and elastic modulus of cp Ti are significantly lower than those of Ti G5; however it is still high when compared to bone (10–30 GPa) and may be about 3–6 times higher than those of cortical bone. Finite element simulations show that materials with lower elastic moduli have better stress distribution at the implant–bone interface and lead to less bone atrophy. A high difference between the moduli of elasticity of the implant material and bone can induce stress shielding, i.e. insufficient transfer of stress to the bone due the high modulus of the prosthesis [8].

Although the mechanical strength of implants is important, they must also present adequate stiffness to avoid shielding the bones from stress. To understand the stress shielding phenomenon, it is necessary to understand that the human body tends to reduce or eliminate their own parts when they are not used. The muscle mass, for instance, is increased by exercise; when we do not exercise, the muscle is gradually lost. Stress shielding is a process that occurs when the forces exerted on a member with prosthesis are different from the forces applied to a normal limb. This difference induces the loss of bone density at the site (osteopenia), leading to bone atrophy. A common site for stress shielding is the proximal femoral diaphysis after placement of a femoral prosthesis. The more tightly the stem of the prosthesis fits into the distal medullary canal, the greater the shift of body weight to the prosthetic stem from the proximal femoral cortex. This causes loss of the normal remodeling forces above the level at which the stem is fixated against the endosteal surface of the medullary canal resulting in osteopenia of the proximal femoral diaphysis [8,9]. This can potentially lead to bone loss in the long term and eventual loosening of the device, requiring an early revision surgery.

Although the G5 titanium alloy is stronger than cp Ti, it can release aluminum and vanadium ions. [10] Some manufacturers use Ti G5 for dental implants, but the implants must have a surface treatment in order to improve the corrosion and reduce ion release. Considering that cp Ti is still chosen for demands where corrosion resistance is a priority (e.g. dental implants), and toxic effects of the dissolution of aluminum and vanadium due to corrosion wear of TiG5 are reason for concern, a modified cp Ti grade 4 alloy is proposed. This modified alloy hardened by cold working (Ti G4 Hard) was developed in an effort to merge the excellent mechanical strength of Ti G5 with the corrosion resistance of cp Ti G4.

The purpose of the present work is to compare the mechanical properties and the surface morphology of dental implant and discs samples after acid etching of modified Ti G4 (Ti