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Bioactive coatings on porous titanium for biomedical applications

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ABSTRACT

Commercial pure titanium is a recognized and accepted material for cortical bone tissue substitution. However, stress-shielding phenomena and lack of osseointegration result in significant limitations. This work is focused on the achievement of an effective solution for both problems via fabrication of porous titanium substrates coated with bioactive glass. Substrates were obtained through the space holder technique giving values of stiffness and yield strength compatible with cortical bone tissue to reduce the stress-shielding phenomenon. Titanium substrates were coated with different number of layers of bioactive glass 45S5 by dripping sedimentation. The substrates porosity was characterized by different techniques. Ultrasound, compression and micro-mechanical testing were used for mechanical properties evaluation. After substrates coating, the infiltration ability, coating homogeneity and structural integrity (chipping and cracking) were evaluated for each coating layer. The chemical composition of coating and phases were studied before and after in vitro tests in Simulated Body Fluid. The results showed more homogenous coating, adherence and greater hydroxyapatite growth for the tri-layer system in both dense and porous samples. Besides, the relation of Ca/P was closed to that of stoichiometric hydroxyapatite in the human body. The coated porous titanium could be potentially used in load bearing partial implants with improved osseointegration.

1. Introduction

Diseases and aging influence the bone tissue quality, making a total or partial bone replacement by implants or prosthesis necessary. The implant functionality is affected by several factors: intrinsic properties of materials and components (shape and geometry features); host bone tissue (quality and quantity); and topography, biochemistry and surface energy of the biointerface between the bone and the implant [1]. Additionally, other factors related to the environmental stimulation also affect prostheses behavior, e.g. mechanical stimulation (local and remote), the systemic immunological response (natural and modulated), and/or some medicine, drugs and systemic effects [1]. The biointerfacial properties are the main elements for the correct performance of the system. The goal of implant design is to reach a biofunctional (bone ingrowth and osseointegration) and biomechanical (stiffness and yield strength) equilibrium [2]. Although commercial pure titanium (c.p. Ti) and its alloys are commonly used as bone implants [3], they exhibit some unsolved issues: stress shielding phenomenon and lack of osseointegration [2,4]. The reduction of the implant Young's modulus can be addressed by fabricating porous materials [5–9]. Regarding the improvement of osseointegration, implant surface modifications have been widely performed [2,4–8], by implementing a variety of techniques that involve physical and chemical changes, e.g. controlling the surface roughness or obtaining bioactive surfaces [10].

The success of implants depends on material properties including mechanical behavior, microstructure and surface characteristics [11]. The surface plays an important role in the response of artificial devices in a biological environment making surface modification one of the most common approaches to improve the biocompatibility. Among bioceramics, hydroxyapatite [$Ca_{10}(PO_4)_6(OH)_2$] (HA) is known for its biocompatibility because of its similar chemical crystallographic structure to the mineral phase of living bone [12]. Hydroxyapatite is an osteoinductive, nontoxic, non-immunogenic agent and has the ability to form strong chemical bonds with natural bone [13,14]. According to its chemical formula, HA has a Ca/P molar ratio of 1.67 (5:3) which is close to the Ca/P ratio in bone minerals (between 1.37 and 1.87) [15].

Bioactive glasses (BGs) are being increasingly investigated as promising scaffold materials for bone regeneration since the discovery of 45S5 BG by Larry Hench in 1969 [13]. BGs have a well-recognized superior osteoconductivity, controlled biodegradability, the capability

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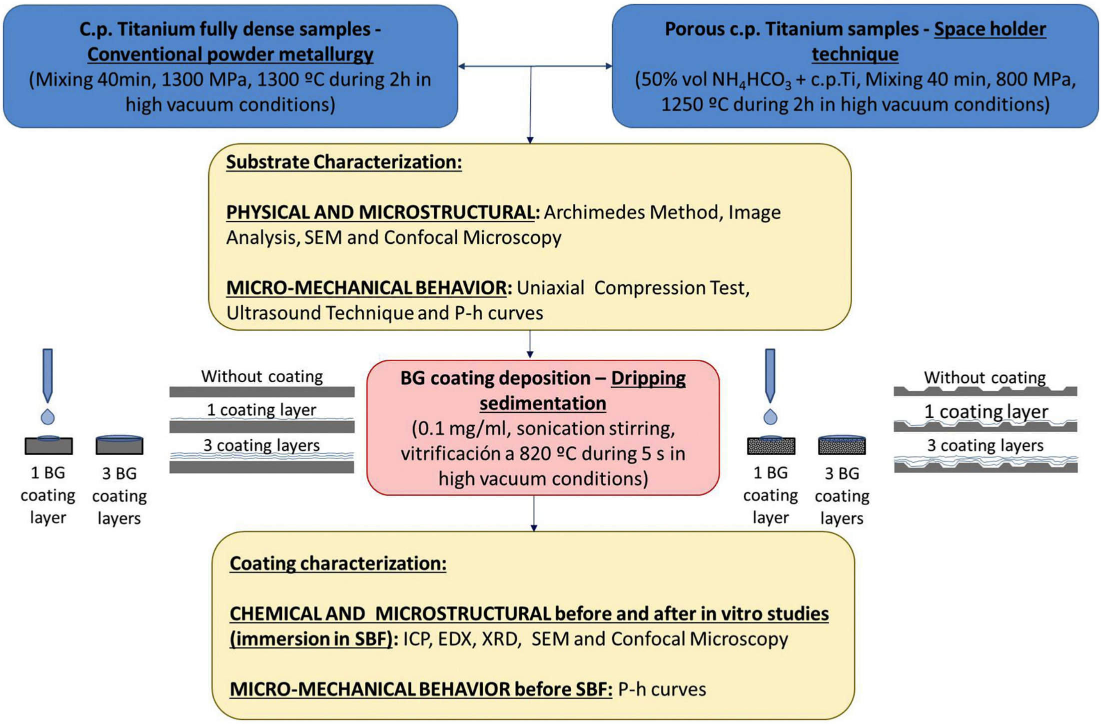

Fig. 1. Experimental procedure: Fabrication and characterization of BG coated titanium substrates.

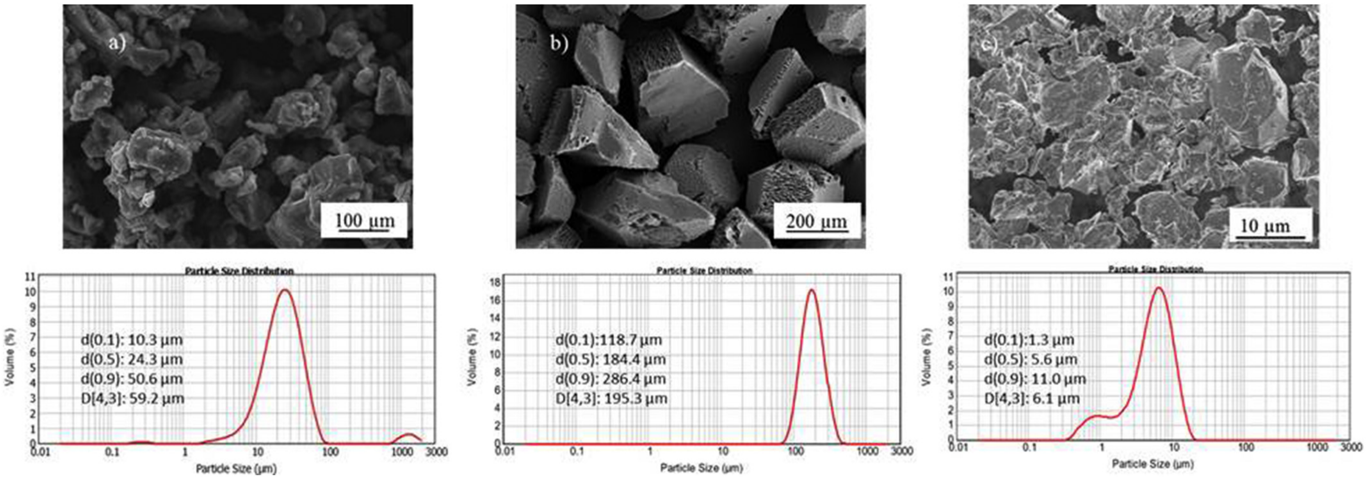

Fig. 2. Particle size distribution of a) Titanium c.p., b) ammonium bicarbonate, c) BG particles.

Table 1
Density and microstructural parameters of titanium substrates.

Substrate	Archimedes' method			Image analysis		
	ρ [g/cm^3]	Porosity (%)		Total porosity (%)	D_{eq} (µm)	F_f
		Total	Interconnected			
Fully dense	4.5	2.4 ± 0.3	0.4 ± 0.2	1.2 ± 0.2	5.5 ± 0.2	~1
Porous	2.4 ± 0.1	47.0 ± 1.0	44.3 ± 1.3	51.8 ± 1.3	161 ± 29	0.7

of activating osteogenic gene expression, angiogenic potential 0 [16], they promote the formation of bone mineral-like phases (including HA) and have drug delivery abilities [14,17]. Bioactive glasses exhibit high bioactivity through the release of dissolution ions such as Ca, P and Si, which may also affect gene expression in osteogenic cells and bone vascularisation, and could lead to the subsequent promotion of a high rate of bone formation [16]. A. Scislowska-Czarnecka et al. [18] tested the effect on macrophage activation after coating porous titanium substrates with BG by sol-gel technique, and compared it to different ceramic coatings. It was found that more cells were adhered to BG-Ti system than to other combinations, as well as to Ti substrate with no covering. The BG coating on porous titanium showed also good