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ScienceDirect

Acta Biomaterialia 5 (2009) 2258–2269

Acta BIOMATERIALIA

www.elsevier.com/locate/actabiomat

Enhanced osseointegration of grit-blasted, NaOH-treated and electrochemically hydroxyapatite-coated Ti–6Al–4V implants in rabbits

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Received 25 November 2008; received in revised form 8 January 2009; accepted 26 January 2009
Available online 3 February 2009

Abstract

Osseointegration, in terms of the bone apposition ratio (BAR) and the new bone area (NBA), was measured by backscattered electron imaging. The results were compared for four implant types: grit-blasted and NaOH-treated Ti–6Al–4 V (Uncoated-NaOH), electrodeposited with hydroxyapatite without alkali treatment (ED-HAp), electrodeposited with hydroxyapatite after alkali treatment (NaOH-ED-HAp), and plasma sprayed with hydroxyapatite (PS-HAp). No heat treatment was done after soaking in NaOH. The implants were press fitted into the intramedullary canal of mature New Zealand white rabbits and analyzed, both at the diaphyseal and at the metaphyseal zones, either 1 week or 12 weeks after surgery. NaOH-ED-HAp already exhibited a higher BAR value than the ED-HAp at 1 week, and was as good as the commercial PS-HAp at 12 weeks. The NBA value for NaOH-ED-HAp at 12 weeks was the highest. The higher content of octacalcium phosphate in NaOH-ED-HAp, as evident from the X-ray photoelectron spectroscopy analysis of the oxygen shake-up peaks, and the associated increase in the solubility of this coating in vivo are considered responsible for the enhanced osseointegration. Taking into account also the reduced occurrence of delamination and the inherent advantages of the electrodeposition process, electrodeposition of HAp following soaking in NaOH may become an attractive alternative for the traditional plasma-sprayed process for coating of orthopedic and dental implants.

Keywords: Hydroxyapatite coating; Electrochemistry; Plasma spraying; Osseointegration; In vivo test

1. Introduction

A key factor for the successful fixation of cementless implants used for joint reconstruction is the establishment of a stable interface between the implant and bone. Coating of the implant with osteoconductive hydroxyapatite (HAp, $Ca_5(PO_4)_3(OH)$) is a well-known method for achieving such fixation [1]. It has been shown that, for consistent performance, HAp coatings should have a proper value of porosity, high cohesive strength, good adhesion to the substrate, moderate to high crystallinity, and high chemical and phase stability [2].

HAp-related bone formation is believed to begin with surface dissolution of the HAp, which releases calcium and phosphate ions into the space around the implant. Reprecipitation of carbonated apatite then occurs on the coating surface [3]. The HAp binds serum proteins and cellular integrin receptors, allowing osteoblastic cells to bind to the surface [4,5]. Bone formation follows at both the bone and the coating surfaces [6]. Bone ongrowth develops more rapidly on coatings with low crystallinity because the

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doi:10.1016/j.actbio.2009.01.033

initial dissolution and release of calcium ions is faster than those associated with coatings of high crystallinity [5,7]. Surface dissolution is therefore a driving force for bone formation, yet the effect of surface roughness on bone apposition may be more significant. It has been shown that rough surfaces exhibit stronger interfaces with bone than do smooth surfaces, in both humans and animals, as long as the interface is bone ongrowth [8,9].

HAp coatings are applied commercially mainly by the plasma-sprayed (PS) process [6]. Since the 1990s, however, much interest in electrodeposition (ED) has evolved [10–20] due to: (i) the low temperatures involved, which enable formation of highly crystalline deposits with low solubility in body fluids and low residual stresses; (ii) the ability to coat porous, geometrically complex or non-line-of-sight surfaces; (iii) the possible improvement of the substrate/coating bond strength; (iv) the ability to control the thickness, composition and microstructure of the deposit; and (v) the ability to incorporate biological matter in the coating during its processing.

Wang et al. [16] studied the osseointegration of uncoated, PS-HAp-coated and ED-HAp-coated Ti–6Al–4V in a canine trabecular bone at 6 h, 7 days and 14 days post-implantation. The PS-HAp was found to provide higher bone apposition ratio than those exhibited by the bare alloy and ED-HAp at 7 days post-surgery. However, at 14 days post-surgery the ED-HAp and PS-HAp coatings exhibited similar bone apposition ratios, much higher than that of the uncoated alloy. This behavior was explained in terms of the lower crystallinity, and consequently higher solubility, of the PS coating compared to the ED coating.

Two shortcomings of the study described in Ref. [16] are: (i) the poor adhesion of the ED-HAp to the metal substrate due to the absence of surface pretreatment; and (ii) the relatively short times of implantation. The objective of the present investigation was to overcome these shortcomings whilst providing insights on the combined effects of grit blasting and soaking in NaOH before electrochemical deposition of HAp.

Grit blasting was applied to either improve the osseointegration of the uncoated implants or increase the adhesion of the ED-HAp coating to the Ti–6Al–4V substrate. Several benefits of this treatment have already been demonstrated elsewhere [21–24].

Soaking of titanium and its alloys in aqueous solution of 5 M NaOH at 60 °C for 24 h and subsequent heat treatment (usually, at 600 °C for 1 h) has been found to form a bioactive surface that spontaneously induces nucleation of bone-like apatite in vivo [25–30]. Similarly, it was hypothesized that this process would lead to enhanced nucleation of the synthetic ED-HAp coating, resulting in increased coating/substrate adhesion strength.

Although most studies have applied heat treatment, and sometimes even found it mandatory in order to achieve good performance [27], it was decided to omit this stage in the present study because such treatment might result in degradation of the mechanical properties of the metal substrate. Regarding the implantation period, it has been argued that healing periods longer than 4 weeks do not further increase the quantity of bone ingrowth into implants with porous surfaces [31]. On the other hand, while HAp-coated implants inserted into cortical bone have been reported to achieve their maximum bone apposition 4 weeks post-implantation, uncoated surfaces were found to increase their bone apposition ratios until 12 weeks [32]. Hacking et al. [33] also argued that 12-week implantation has a clinical value. Therefore, the selection of this implantation period in the present work should allow for complete osseointegration of both coated and uncoated implants, thereby allowing for precise comparative study.

2. Materials and methods

2.1. Implant preparation

A Ti–6Al–4V ELI grade rod (ASTM F136-02a) rod, 4.76 mm in diameter, was produced by Dynamet, Inc. (Washington, PA) and supplied by Barmil (Petach-Tikva, Israel). This rod was machined into 25-mm-long sample rods that were subsequently cleaned with paper and MEK, then ultrasonically in acetone. Twelve rods were plasma sprayed with 80-μm-thick HAp. This group will be termed hereafter PS-HAp. Thirty-six rods were chemically etched in HF/HNO_3 solution for 2 min, washed with DI water, dried and then grit-blasted (GB) with high-purity (98.2%) white alumina powder from Calbex Mineral Trading, Inc. (Henan, China). The blasting parameters were: grit size of F200–F180 (59–68 μm), pressure of approximately 6 atm and working distance of about 10 cm. Blasting with alumina powder was preferred over blasting with silica powder because of biocompatibility aspects. After grit blasting, the rods were cleaned ultrasonically. Twelve of these rods were subsequently electrodeposited with HAp; these will hereafter be referred to as ED-HAp. The remaining 24 rods were soaked in a stirred solution of 5 M NaOH at 60 °C for approximately 14 h. Afterwards, they were cleaned ultrasonically in acetone and then in ethanol, washed with Millipore water (Milli-DI™, Millipore Corporation, Billerica, MA), dried and then kept in a clean environment. Complementary heat treatment was not applied. Of these rods, 12 were left uncoated; these will hereafter be referred to as Uncoated-NaOH. The last 12 rods were subsequently electrodeposited with HAp; these will hereafter be referred to as NaOH-ED-HAp.

Electrodeposition was carried out in a standard three-electrode cell in which two graphite rods were used as the auxiliary electrode, a saturated calomel electrode (SCE) was used as the reference electrode and the sample rod was used as the working electrode. The electrolyte was prepared by dissolving 0.61 mM $Ca(NO_3)_2$ and 0.36 mM $NH_4H_2PO_4$, both AR-grade from Merck (Darmstadt, Germany), in Millipore water. The acidity was measured using an InoLab pH/Oxi Level 3 meter (WTW GmbH, Weilheim, Germany) and adjusted to pH 6.0 so that the electro-