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Research Paper

Mechanical performance of a biocompatible biocide soda–lime glass-ceramic

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ABSTRACT

A biocompatible soda–lime glass-ceramic in the SiO_2–Na_2O–Al_2O_3–CaO–B_2O_3 system containing combeite and nepheline as crystalline phases, has been obtained at 750 °C by two different routes: (i) pressureless sintering and (ii) Spark Plasma Sintering. The SPS glass-ceramic showed a bending strength, Weibull modulus, and toughness similar values to the cortical human bone. This material had a fatigue limit slightly superior to cortical bone and at least two times higher than commercial dental glass-ceramics and dentine. The *in vitro* studies indicate that soda–lime glass-ceramic is fully biocompatible. The *in vivo* studies in beagle jaws showed that implanted SPS rods presented no inflammatory changes in soft tissues surrounding implants in any of the 10 different cases after four months implantation. The radiological analysis indicates no signs of osseointegration lack around implants. Moreover, the biocide activity of SPS glass-ceramic *versus Escherichia coli*, was found to be >4 log indicating that it prevents implant infections. Because of this, the SPS new glass-ceramic is particularly promising for dental applications (inlay, crowns, etc).

1. Introduction

Bacterial resistance to antibiotics is a widely-studied, long-established problem (Costerton et al., 1999). Increasingly, attention is being focused on the responses of various categories of microorganisms to biocides (antiseptics, disinfectants and preservatives). Drug resistance in bacteria is increasing and the pace at which new antibiotics are being produced is decreasing (Russell, 2002). Reduced susceptibility to biocides is also apparently increasing, but is more likely to be at low-level in nature and to concentrations well below than those used in hospital, domestic and industrial practices. A particular problem is found with bacteria and other micro-organisms present in biofilms, where a variety of factors can contribute to a greater resistance to biocides compared with cells in planktonic culture (Lewis, 2001).

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This is significant not only environmentally, *e.g.* biofouling and biocorrosion, but also with implanted medical devices, infection of which may be difficult to eradicate.

At present, the most important research activity on inorganic biocides is in the fields of Nanoscience and Nanotechnology, focused specifically on materials supporting silver or copper nanoparticles (Miranda et al., 2012; Miranda Fernández et al., 2010; Kim et al., 2007; Lin et al., 1996, 1998). However, at the same time, there is a negative impact of metal based nanomaterials – engineered metal and metal oxide nanoparticles – to human health (Gwinn and Vallyathan, 2006). The limits of such toxic health effects are still unknown (Wang et al., 2013).

With the aim of avoiding these risks, a new generation of biocides has recently been developed as very efficient "green" antimicrobials with no adverse effects on the environment (Moya et al., 2011). They are based on soda–lime glass powders, a very abundant material, with a composition similar to that of classical window glass. These glass powders, conveniently processed by being enriched with CaO, have been converted into a high added-value material suitable for application in several strategic fields in which the control of unwanted heterogeneous microbial population represents a serious threat to human kind. The results obtained have been unexpectedly high; the biocide activities of these glass powders were evaluated against Gram-positive bacteria (*Micrococcus luteus*), Gram-negative bacteria (*Escherichia coli JM 110*) and yeast (*Candida krusei*). The unexpected high biocide activity observed was very encouraging. It has been emphasized that their use on some applications might well be an alternative to highly aggressive commercial organic biocides, for example the chlorinated aromatic (*Triclosan*) or inorganic compounds such as silver and copper nanoparticles. Additionally, these powders are stable environmental agents and their biocide activity relies on their close contact with the target cells. Moreover, as all of their components are a natural part of the soil, they are environmentally friendly.

The behavior of this material has also been investigated as glass-ceramic coating on different substrates (titanium alloy and zirconium oxide) (Esteban-Tejeda et al., 2013) for dental applications (Pavon et al., 2006).

Up to now, the research found in the literature on hard tissue substitution (craniofacial, orthopedic and oral implantology) has concentrated on the mechanical performance of the biomaterials developed (Chevalier and Gremillard, 2009; Chevalier et al., 2011; Torrecillas et al., 2009; Gutiérrez-González et al., 2012). Nowadays, the approach is much more ambitious, as the aim is to obtain materials similar to those that are to be replaced. That involves a multifunctional character that combines properties such as biocide activity, biocompatibility, bioactivity, ability to avoid the formation of biofilm, osseointegrability, non-toxicity, *etc.* (Lindfors et al., 2010; Nganga et al., 2013; Zhang et al., 2012). Moreover, a good mechanical performance is still mandatory, as similar as possible to that of the materials to be replaced. For instance, in the case of materials for knee, hip or teeth implants, the mechanical properties of the ideal material have to be close to those of bone, *i.e.*, low elastic modulus (20 GPa), adequate flexural resistance (150–200 MPa), good fatigue resistance, etc.

Therefore, in our work, after the sets of results obtained from the precursor glass powder and the glass-ceramic coatings, the next step considered has been to study the behavior of the bulk material to see if it qualifies for such multifunctional biomaterial applications. Thus, the objectives of this work are to study the glass-ceramic compacts obtained by two different processing routes: pressureless sintering and Spark Plasma Sintering. The study has been focused in terms of mechanical performance, bioactivity and biocide character.

2. Material and methods

2.1. Powder processing and microstructural characterization

An antimicrobial soda–lime glass powder ($d_{50}=35\pm5\ \mu m$) from the SiO_2–Na_2O–Al_2O_3–CaO–B_2O_3 system with the following chemical composition was used (wt%): 41.6 SiO_2, 20.0 Na_2O, 19.5 CaO, 10.1 Al_2O_3, 6.4 B_2O_3, 0.21 MgO and 0.61 K_2O (*Sovitec Iberica*, Barcelona, Spain). Two consolidation methods were followed to fabricate the samples: (i) Pressureless sintering and (ii) Spark Plasma Sintering (SPS). In the first case, the precursor powders were cold isotactic pressed (CIP) at 300 MPa as cylinders with 15 mm in diameter and subsequently sintered in a conventional furnace in air at 750 °C for 1 h. In the second method, the powders were sintered by SPS in vacuum at 750 °C for 3 min at 32 MPa (*FCT Systeme GMBH*, HPD 25, Germany) as 20 mm diameter disks.

A mineralogical characterization of the samples sintered by both methods was made by X-Ray Diffraction (XRD, Bruker AXS D8 ADVANCE, with a SolX energy-dispersive detector) using CuK_α radiation on the surface of the samples. The microstructure of sintered specimens after polishing down to 1 μm was studied by Scanning Electron Microscopy (FE-SEM, FEI Nova NANOSEM 230).

2.2. Flexural strength and elastic modulus

The flexural strength and elastic modulus were studied by 3-point bending tests on parallelepipeds of dimensions $3\times4\times18\ mm^3$ machined from both the cylinders obtained by conventional sintering and the discs obtained by SPS. The tests were performed at room temperature using a 5 kN universal testing machine *Shimadzu* AutoGraph AGX (Kyoto, Japan) at a crosshead speed of 1 mm/min with 12.5 mm span.

Strength variation among each group was evaluated by calculating the Weibull modulus (*m*). A computer was used to rank the strength data in ascending order and appoint a rank over the range 1–*N* (*N* is the number of specimens); a straight line was then fitted through the points using the median rank regression method. The following equation was used to calculate the Weibull modulus, as follows:

$$P_f = 1-\exp[-(\sigma/\sigma_0)^m] \quad (1)$$

where P_f is the failure probability, σ is the strength at a given P_f; σ_0 is the characteristic strength and m is the Weibull modulus. However, since σ_f can be identified by the following relation:

$$P_f = j/(N+1) \quad (2)$$