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A new technological procedure using sucrose as porogen compound to manufacture porous biphasic calcium phosphate ceramics of appropriate micro- and macrostructure

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Abstract

In the domain of implantable materials, the porosity and pore size distribution of a material in contact with bone is decisive for bone ingrowth and thus the control of the porosity is of great interest. The use of a new porogen agent, *i.e.* sucrose is proposed to create a porosity in biphasic calcium phosphate blocks. The technological procedure is as follows: sucrose and mineral powder are mixed, then compressed by isostatic compression and sintering finally eliminates sucrose. Blocks obtained were compared to a manufactured product: Triosite® (Zimmer, Etupes, France) which porosity is created through a naphthalene sublimation process.

Results have shown that the incorporation of sucrose allows the preparation of porous blocks with controlled porosity varying from 40 to 80% and with macro-, meso- and microporosity characteristics depending on the percentage of sucrose added as well as on the granulometry of both sucrose and mineral powder.

Keywords: B. Porosity; B. Electron microscopy; Mercury porosimetry; Calcium phosphate ceramics

1. Introduction

Due to their chemical composition close to the bone mineral (biological apatite), the main bioactive ceramics used for implants are calcium phosphate ceramics (CaP). The efficiency of such CaP ceramics is related to their chemical nature as well as to their porous structure. To be invaded by bone ingrowth and to allow body fluid circulation, the CaP ceramics have to be porous (total pore volume near 60%), *i.e.* they must contain both macropores of at least 100 μm – most of them lying between 150 and 300 μm – and micropores inferior to 5–10 μm, this last fraction being not greater than 5–10% [1–10]. Therefore, control of porosity within the porous bioceramics is a critical matter. Another problem for these porous structures is their low compression strength and modulus, which are quite different from those exhibited by cancellous bone [10–13].

Many processes have been described for the preparation of porous materials: use of replica sponge structures such as the so-called polymeric sponges (reticulate ceramics) [10,14–16] followed by heat treating, replicas of marine coral [17]; introduction of porogen substances which will create a porous structure after calcination and which integrity is maintained through the sintering step (naphthalene particles [18,19]), organic polymers such as poly vinyl butyral (PVB) [7,20], polystyrene or polymethyl methacrylate beads [6], sodium chloride grains [21], calcium polyphosphate particles [22], cellulosic powder or artificial polymers and binders [11], flour [23], gas-forming (carbon dioxide, hydrogen) agent such as ball-shaped granules of clay (foam ceramics) [14], $CaCo_3$ [24,25], hydrogen peroxide [5] and so on. However, each technique has its own limit: relatively low strength (polymeric sponges, cellulosic powder or artificial polymers and binders), pore size limited to several micrometers ($CaCo_3$, flour), or low permeability in foam ceramics (open and closed voids) when compared to reticulate ceramics (interconnected voids) [14].

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We have already shown [4,26,27] that porous blocks of biphasic calcium phosphate (BCP) with a macroporosity close to 50% (mean pore size of 400–600 μm), a microporosity of about 35% and a 60/40 hydroxyapatite (HA)/tricalcium phosphate β (β-TCP) ratio have a degradation rate adapted to bone ingrowth kinetics. The method employed to create the porosity of these blocks is the Hubbard's one [18], where 50% of calibrated naphthalene particles (mean: 500 μm) were added to 80–200 μm mixed powders of HA and β-TCP. Samples were subjected to isostatic compression (200 MPa) and the resulting blocks were sintered at 1100 °C, after being subjected to a slow thermal ramp (up to 550 °C) in order to eliminate the naphthalene particles by sublimation. However, this method suffers from several drawbacks such as toxicity associated to PAHs, fire setting, air pollution and difficulties of naphthalene grinding and sieving.

The aim of the present study was to test the feasibility of elaborating blocks with a controlled porosity using sucrose particles with different size fractions of 565, 407.5, 257.5 and 150 μm as the porogen agent, the sucrose being associated to the apatite powder at concentration ranging from 35 to 55% (v/v). This compound is cheaper, safer and easier to manipulate than naphthalene. Resulting powder mixtures were submitted to high pressure using isostatic compression, and then sintered. Porosity and pore size distribution were evaluated through scanning electron microscopy (SEM) coupled to image analysis and through mercury porosimetry. Blocks were compared with ceramics obtained after sublimation of naphthalene as the porogen agent [18].

2. Experimental procedures

2.1. Materials

The synthesis of the calcium deficient apatite (CDA) was completed by alkaline hydrolysis of dicalcium phosphate dehydrated (DCPD, Merck, France) [28]. Crystalline sucrose (Beghin Say, France), used as the porogen compound, was previously mechanically sieved (503 502 Sieve, Fristch Laborgerätebau, Germany) on 630, 500, 315, 200 and 100 μm sievers for 20 min to collect 565, 407.5, 257.5 and 150 μm grains. CDA granules were obtained as follows: The CDA powder was introduced in an elastomer mold under vacuum, then the mold was transferred into a high-pressure chamber containing water and subjected to isostatic compression under 200 MPa during 2 min according to a protocol previously described [29]. Briefly, the pressure was increased to 200 MPa (3.4 MPa s^{-1}) for 2 min, then slowly decreased (1.2 MPa s^{-1}) to the atmospheric pressure using an hyperbar equipment (Alstom, Nantes, France).

The resulting compressed blocks of CDA were sintered in a controlled-temperature Vecstar furnace (Vecstar, Eurotherm, Suisse) according to the following process. The temperature was first raised to 180 °C (2 °C min^{-1}) for 240 min, then to 560 °C for 300 min in order to eliminate sugar particles, and finally to 1050 °C (3 °C min^{-1}) for 300 min. Then the blocks were cooled down to 25 °C (3 °C min^{-1}), crushed in a grooved roller breaker (TG2S, Erweka Apparatebau GmbH, Germany) and mechanically sieved for 20 min to collect 565, 407.5, 257.5 and 150 μm granules.

2.2. Block formulation

Two experimental studies were performed in parallel. In the first one, different percentages of sucrose: 35, 45 and 55% (v/v) of each granulometry (565, 407.5, 257.5 and 150 μm) were added to 65, 55 and 45% (v/v) of the synthetic CDA powder (samples 1–12), respectively. In the second one, 45% (v/v) of sucrose granules were added to 55% of CDA granules, each having the same granulometry (565, 407.5, 257.5 or 150 μm) (samples 13–16). The mixing (weight: around 80 g) were elaborated using a Turbula® (T2C, WAB, Suisse) for 3× 5 min. Each mixing was conditioned in an elastomer mold under vacuum. The mold was then isostatically compressed in a hyperbar equipment. The resulting compressed blocks of CDA and porogen were sintered in a controlled-temperature Vecstar furnace (Vecstar, Eurotherm, Switzerland). These two last operations were conducted according to the aforementioned process (see Section 2.1). Smaller blocks were then sectioned in the central region of the compressed blocks in 5 mm × 5 mm × 5 mm blocks with a diamond saw (Dremel Moto-Flex 732-T1, USA).

2.3. Physicochemical characterization

CDA purity was checked by Fourier transformed Infrared spectroscopy (Nicolet Magnat II 550 FTIR spectrometer, Paris, France) and X-ray diffraction (PW 1730 Diffractometer, Philips, France) [30,31] after sintering at 1050 °C for 5 h in the Vecstar furnace.

2.4. Morphological aspect of porous block

The blocks were embedded in a methylmetacrylate resin using the following protocol: a dehydration step (1 day in ethanol 80% (v/v), 1 day in ethanol 95% (v/v), then 1 day in absolute ethanol) was followed by an impregnation one (1 day in a mixture of absolute ethanol/methylmetacrylate: 1/1, 2 days in destabilised methylmetacrylate and 2 days in methylmetacrylate) and finally a drying step (1 week in an oven at a progressively increasing temperature: 30–80 °C). The impregnated samples were then transversally sectioned in two parts, with a diamond disc (Isomet, type 111180, low speed saw, Buehler, USA). Internal surfaces were polished with a diamond paste to achieve less than 1 μm of roughness. The two surfaces of each sample were then metallised by cathodic pulverisation (Emscope, AEI 230, Ashford, UK) with a gold–palladium complex under a 15 kV voltage (15 min), before SEM analysis (JSM-6300, Jeol, Tokyo, Japan). In those conditions, porous areas appeared in black whereas biomaterial areas varied from white to grey.

2.5. Porosity evaluation

Two methods were performed to evaluate the block porosity. In the first one, SEM was coupled to a semi-automatic image